XXXIII Canary Islands Winter School of Astrophysics

Fundamental Physics with Galaxies (lecture II)

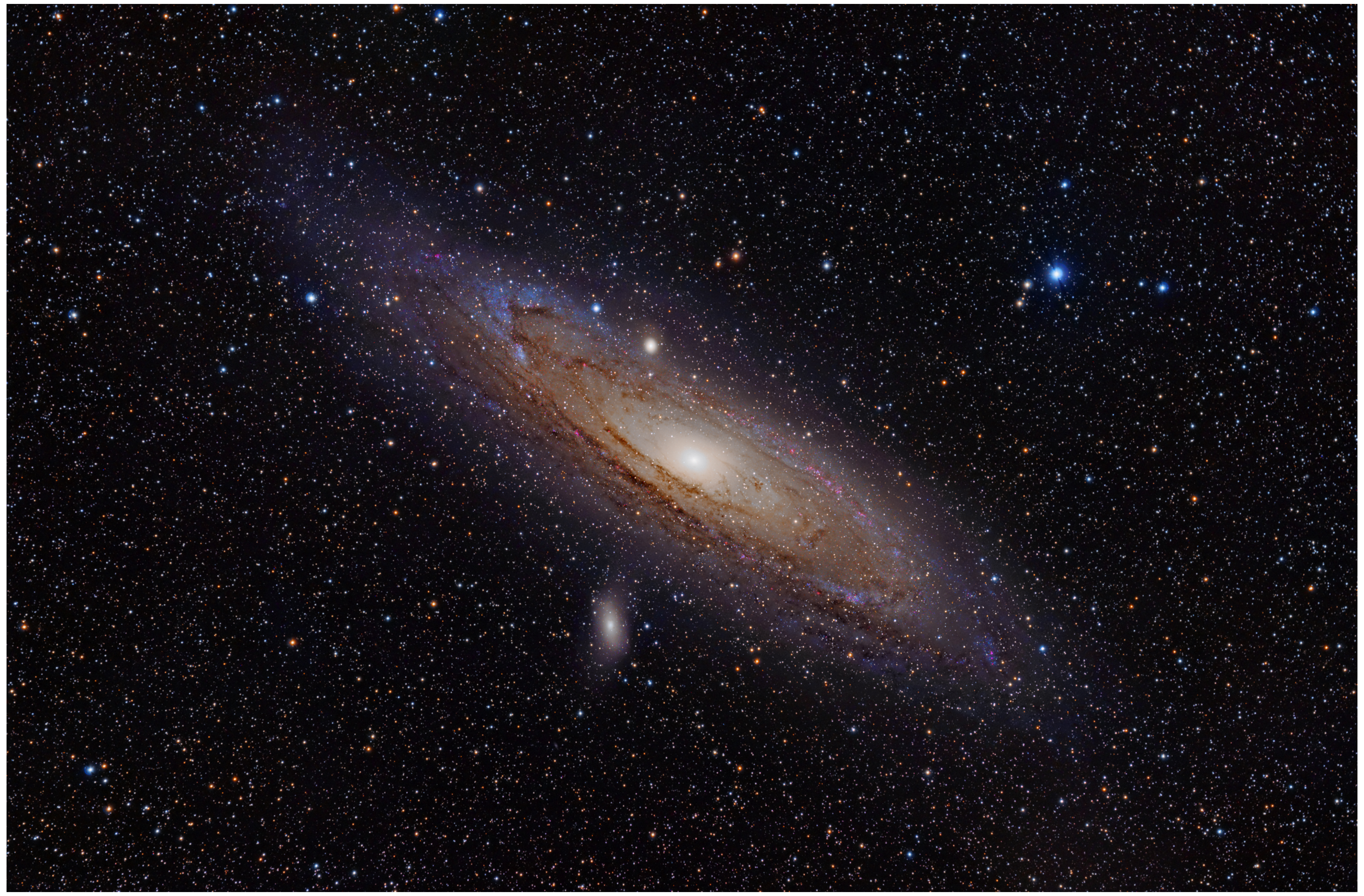
Kfir Blum | Weizmann Institute of Science

Dark matter

m_X

10^{-21} eV

$10^{-10}\ \mathrm{M}_\odot \sim 10^{56}$ eV



Gravity alone

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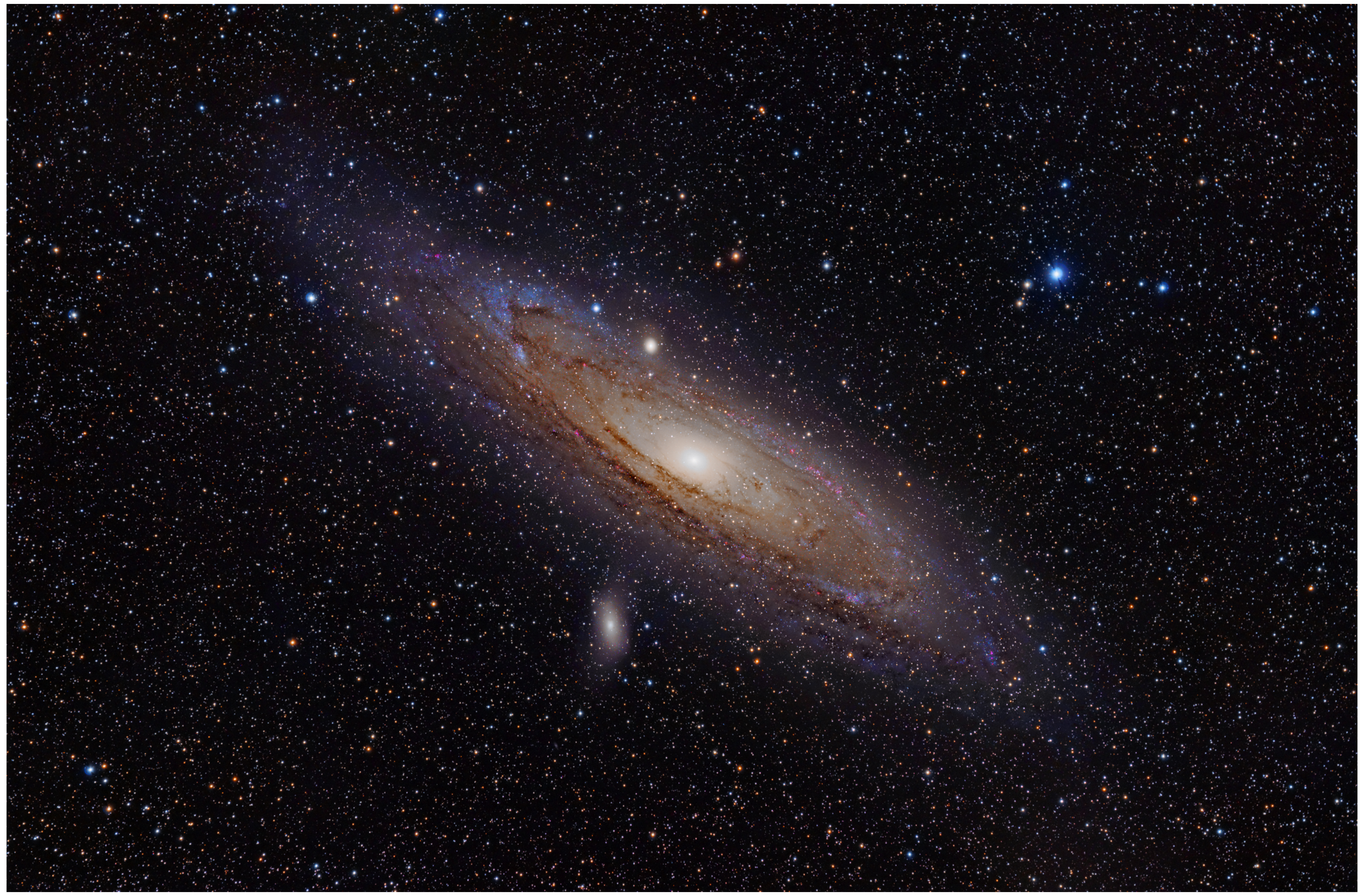

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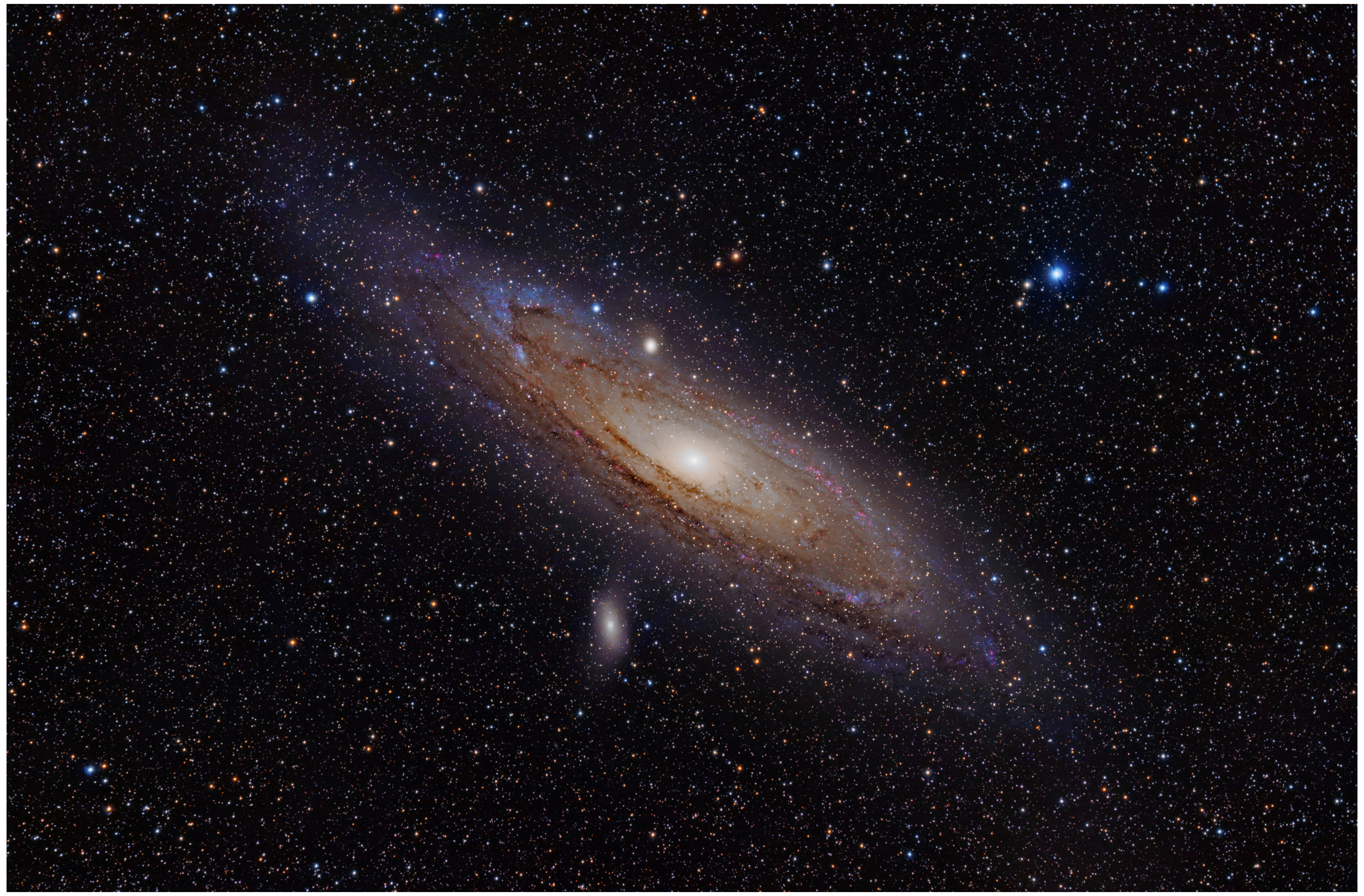
Ultralight dark matter



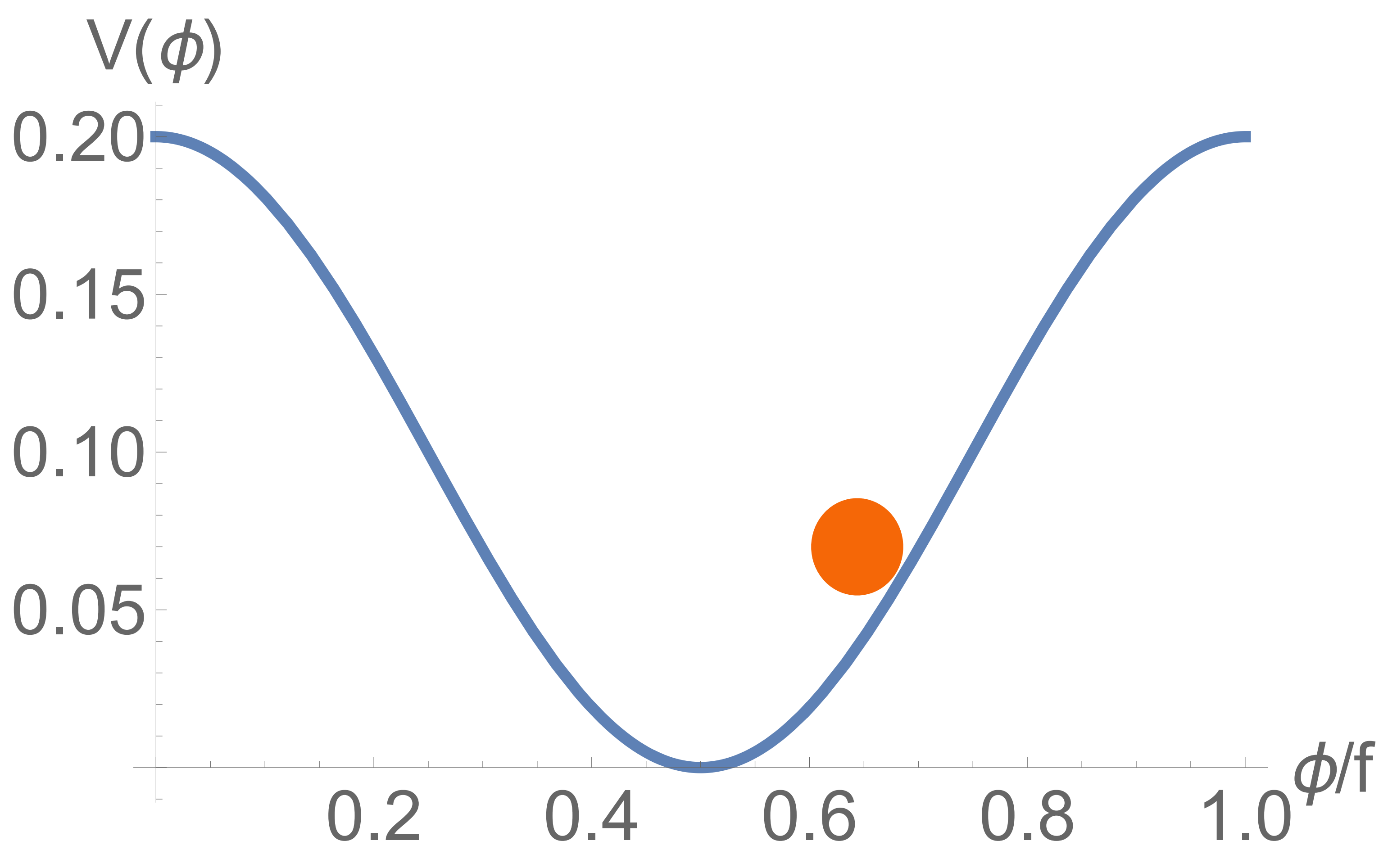
Ultralight dark matter (ULDM)

Light fields (Goldstone bosons) feature in many models. Svrcek & Witten 2006; Arvanitaki et al 2010

Cosmology: field initially displaced from minimum of the potential (before/during inflation)

$$\frac{1}{\sqrt{-g}}\mathscr{L} = \frac{1}{2}g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi + m^2 f^2 \cos\frac{\phi}{f}$$

$$\ddot{\phi} - \frac{\nabla^2}{a^2}\phi + m^2\phi + 3H\dot{\phi} = 0$$



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Starts to oscillate when $t \sim 1/m$.

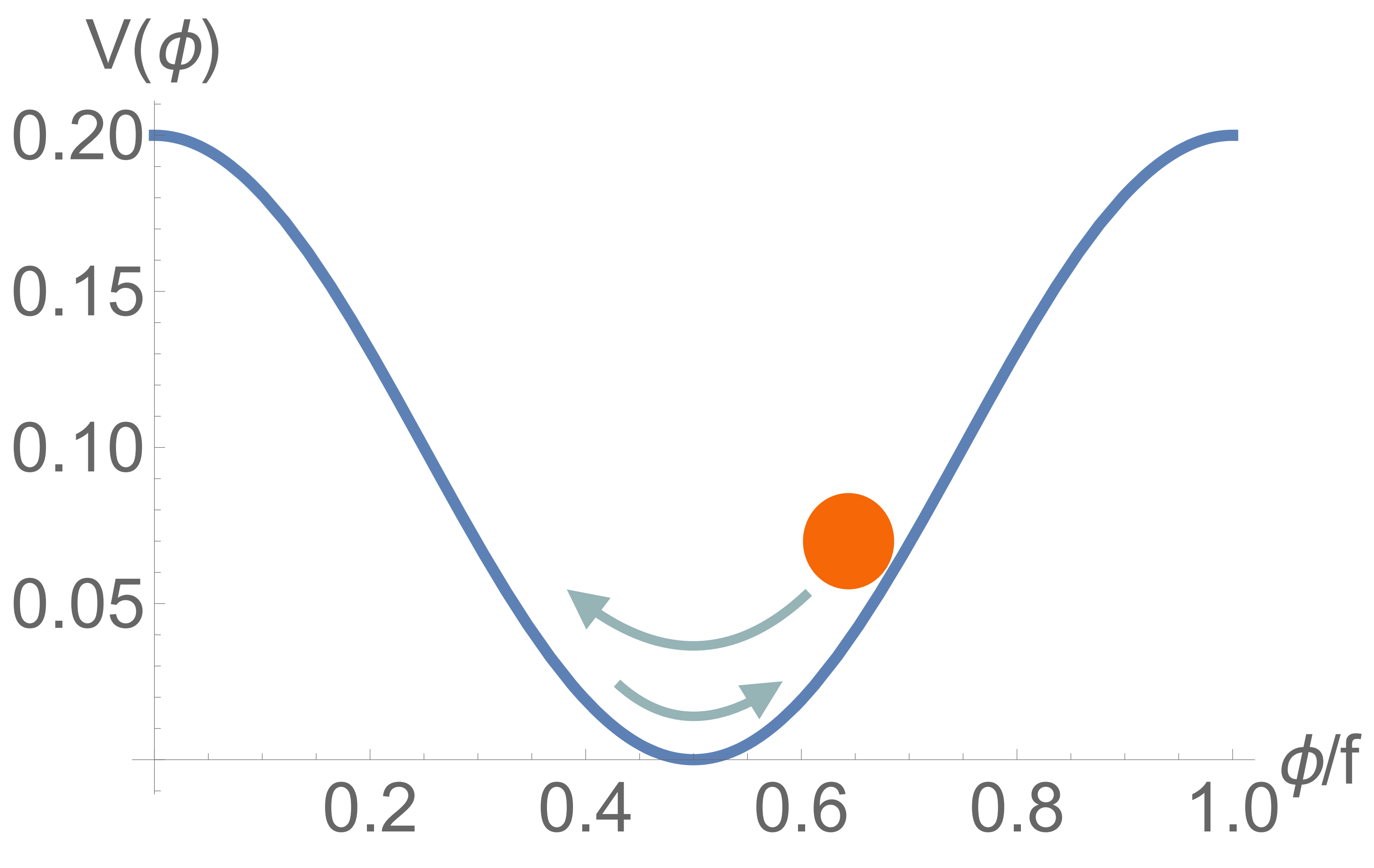
When $t \gg 1/m$, correct equation of state for dark matter.

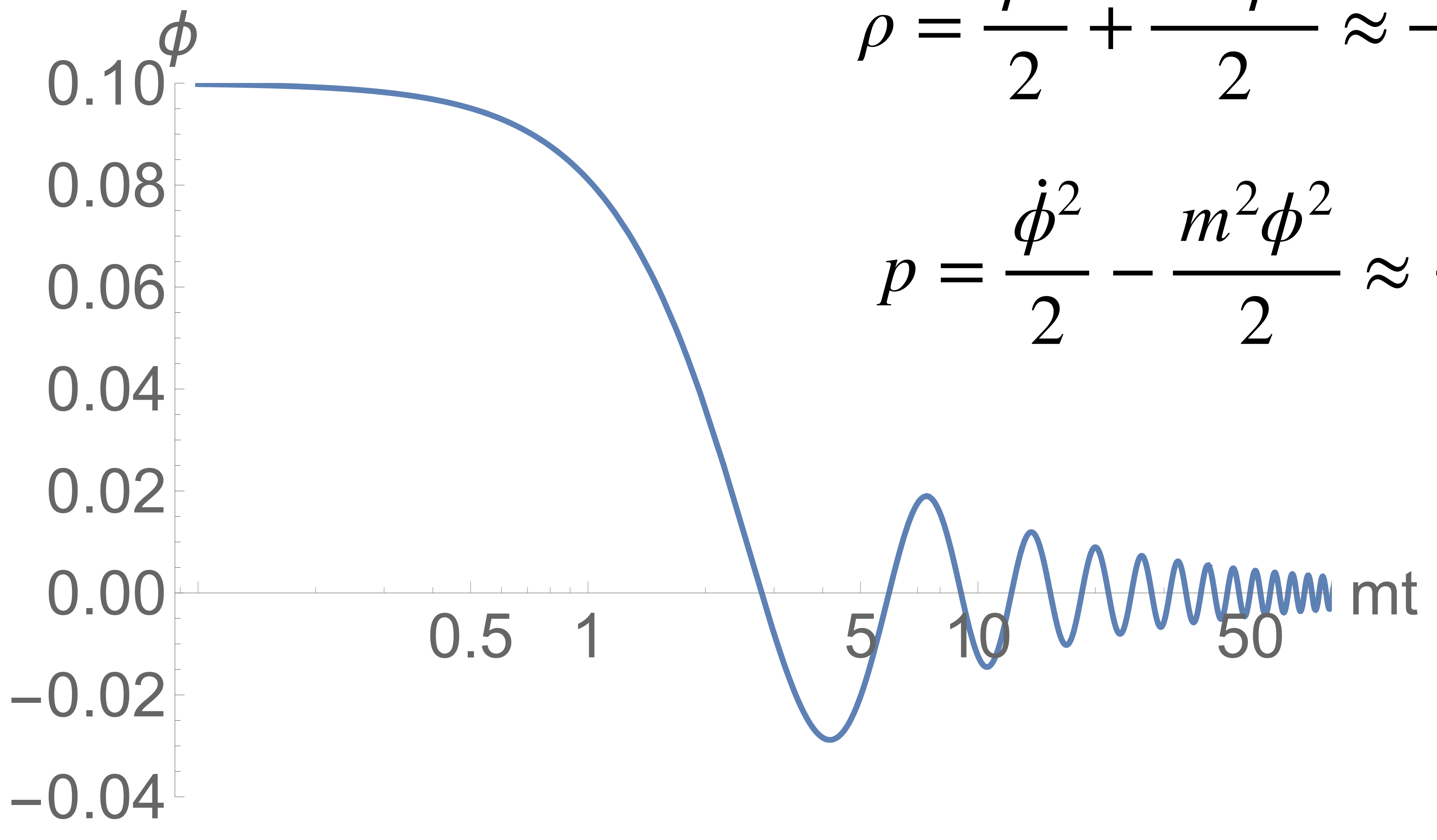
$$\ddot{\phi} - \frac{\nabla^2}{a^2}\phi + m^2\phi + 3H\dot{\phi} = 0$$

When $m \gg H$: $\phi \approx (1+z)^{\frac{3}{2}}\phi_0 \cos mt$

$$\rho = \frac{\dot{\phi}^2}{2} + \frac{m^2\phi^2}{2} \approx \frac{m^2\phi_0^2}{2}(1+z)^3$$

$$p = \frac{\dot{\phi}^2}{2} - \frac{m^2\phi^2}{2} \approx -\rho\cos 2mt$$





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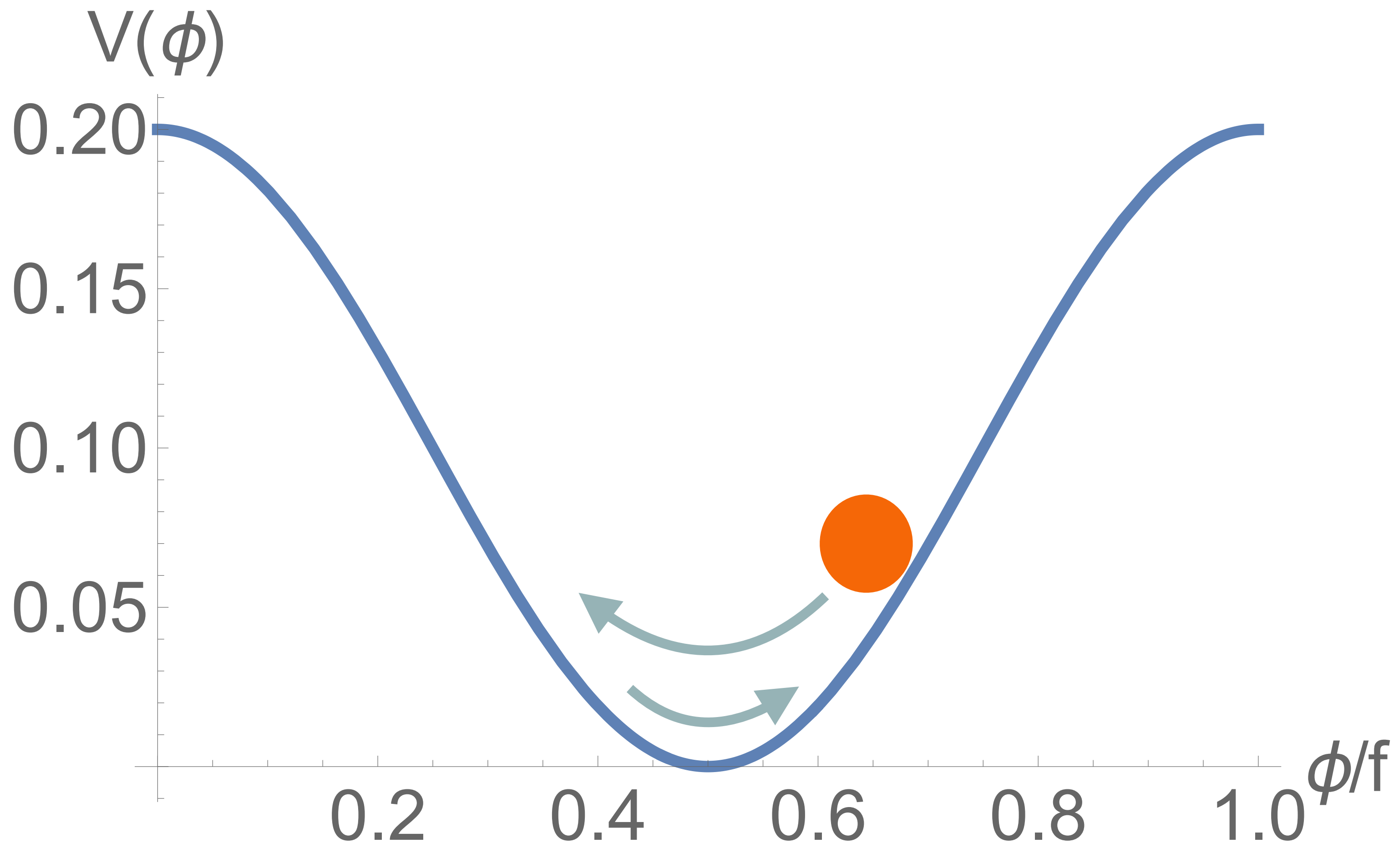
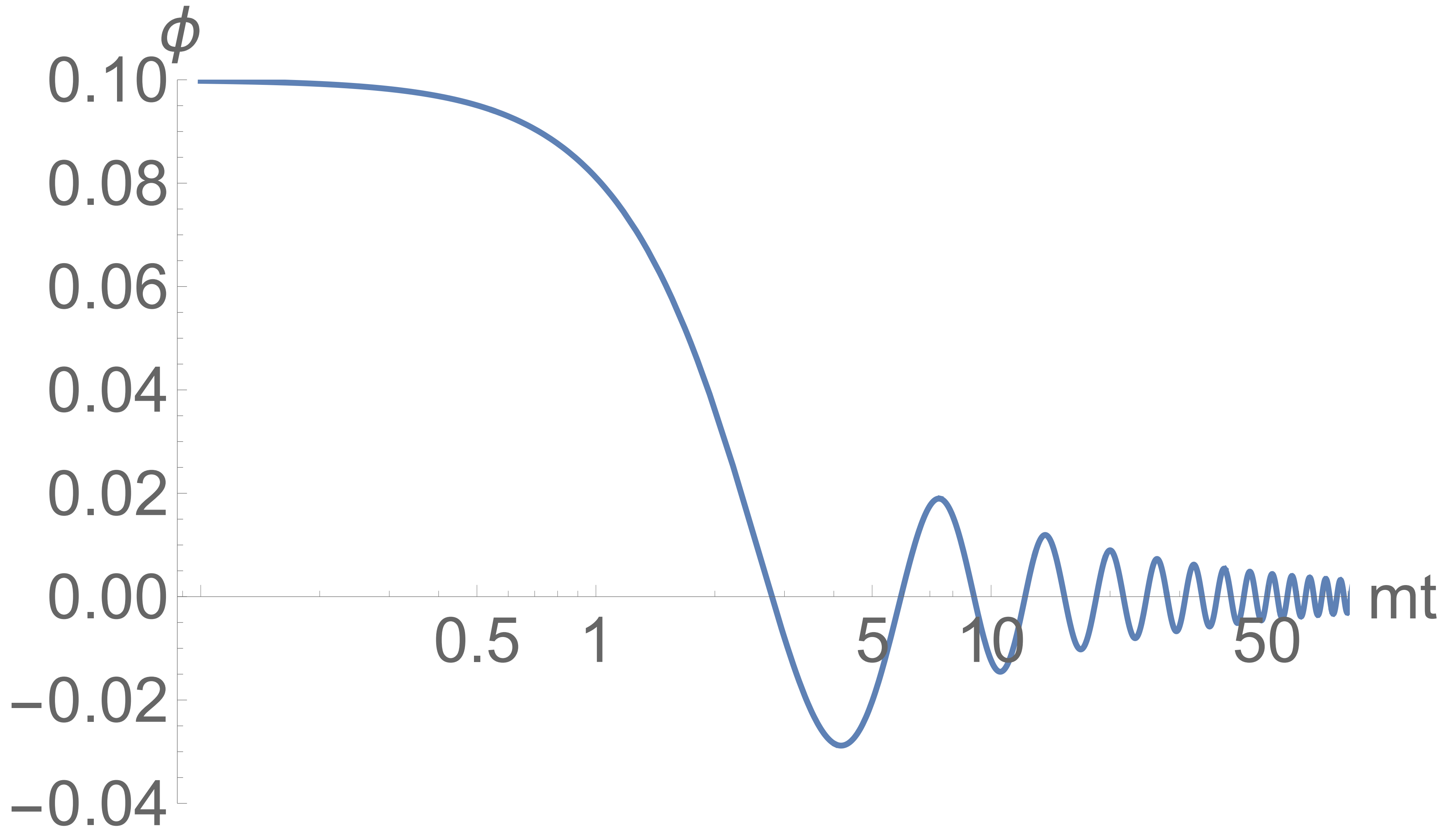
$$\rho(z=0) \approx \frac{\rho(z_m)}{(1+z_m)^3} \approx \frac{\alpha^2 m^2 f^2}{2\,(1+z_m)^3}$$

Contribution to energy density today:





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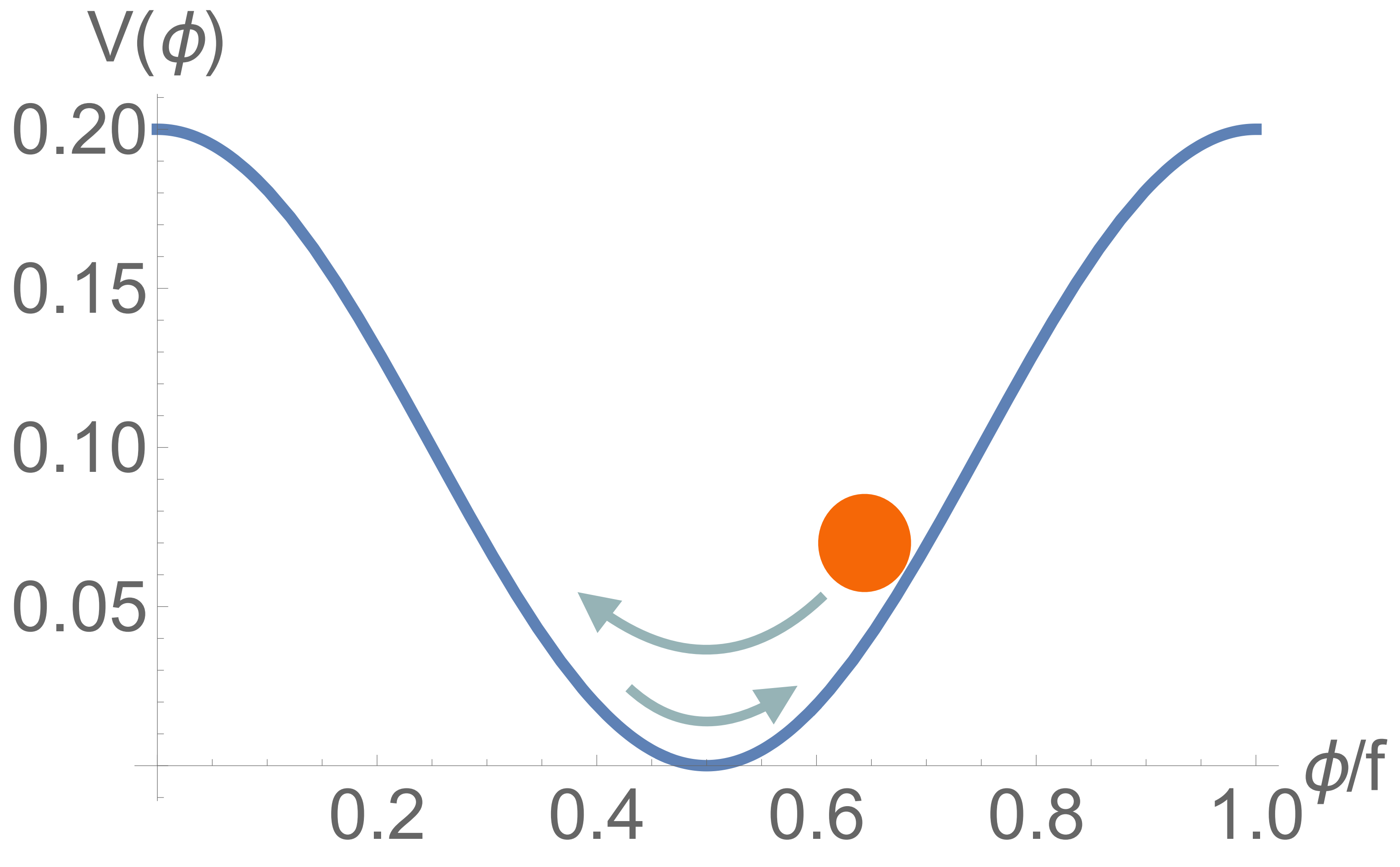
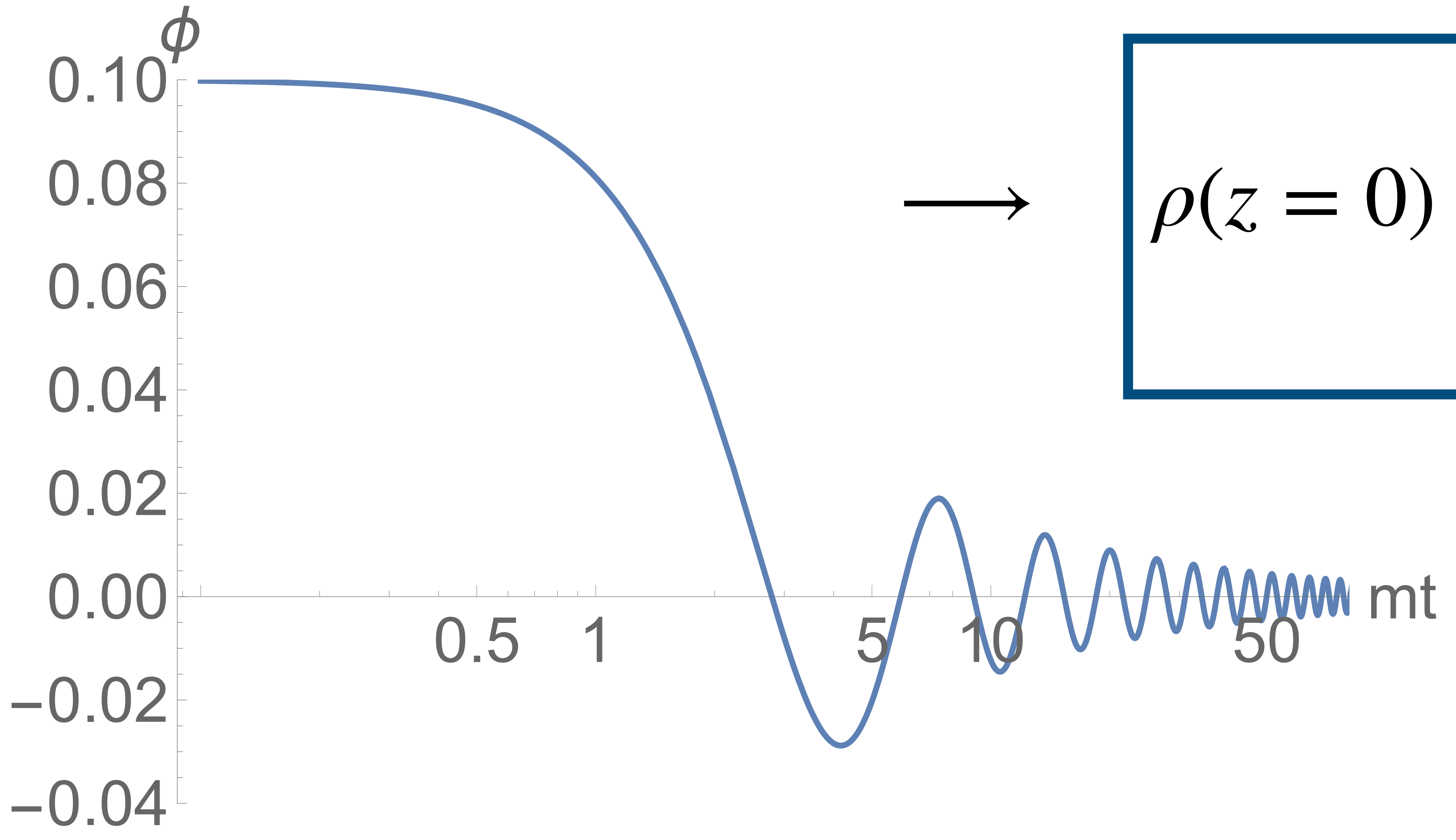
Contribution to energy density today:

$$1 + z_m \approx \frac{T_m}{T_0} \approx \frac{\sqrt{mM_{pl}}}{T_0}$$





$$\longrightarrow \quad \boxed{\rho(z=0) \approx \frac{\alpha^2 T_0^3}{M_{pl}^{\frac{3}{2}}} m^{\frac{1}{2}} f^2}$$

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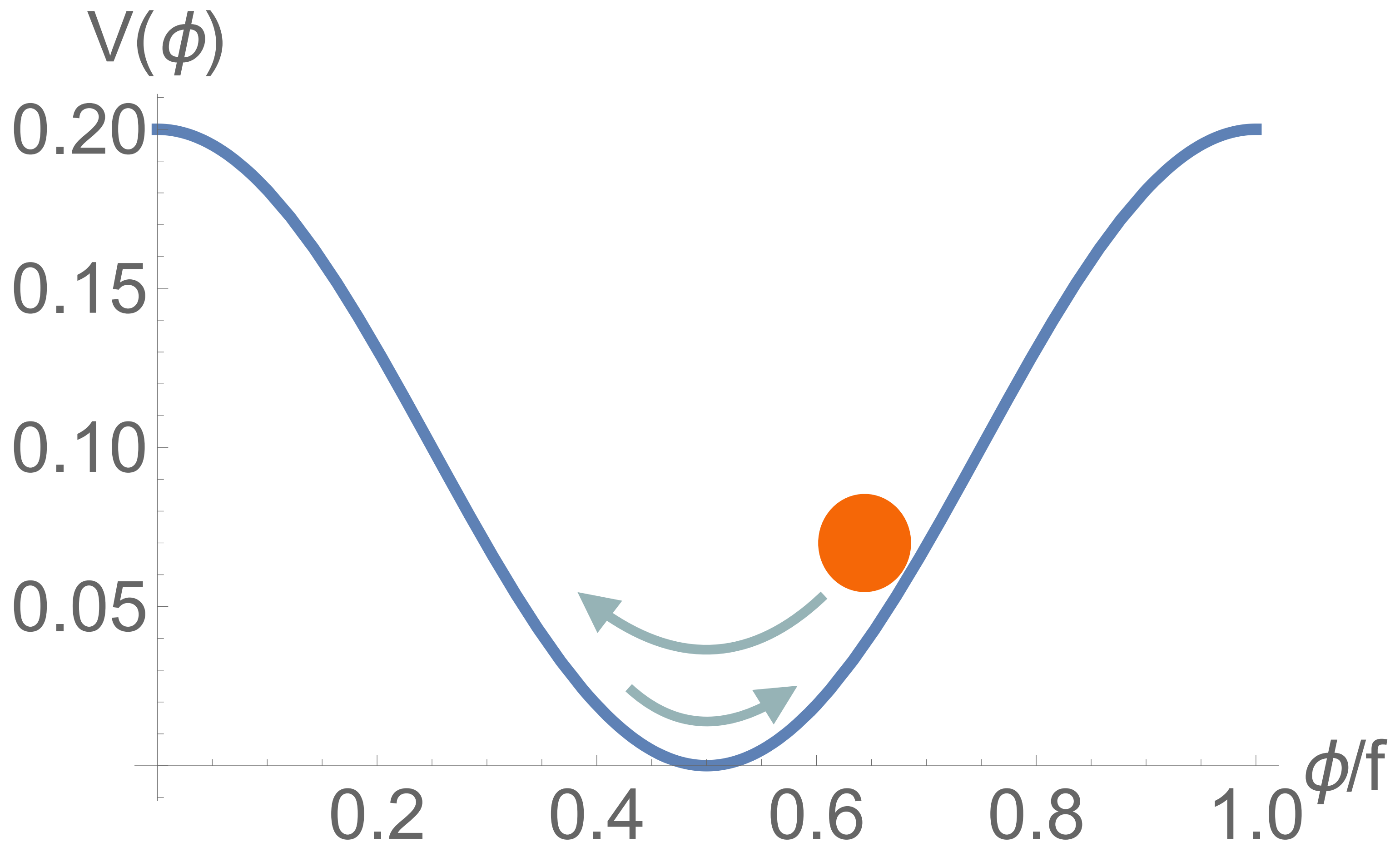

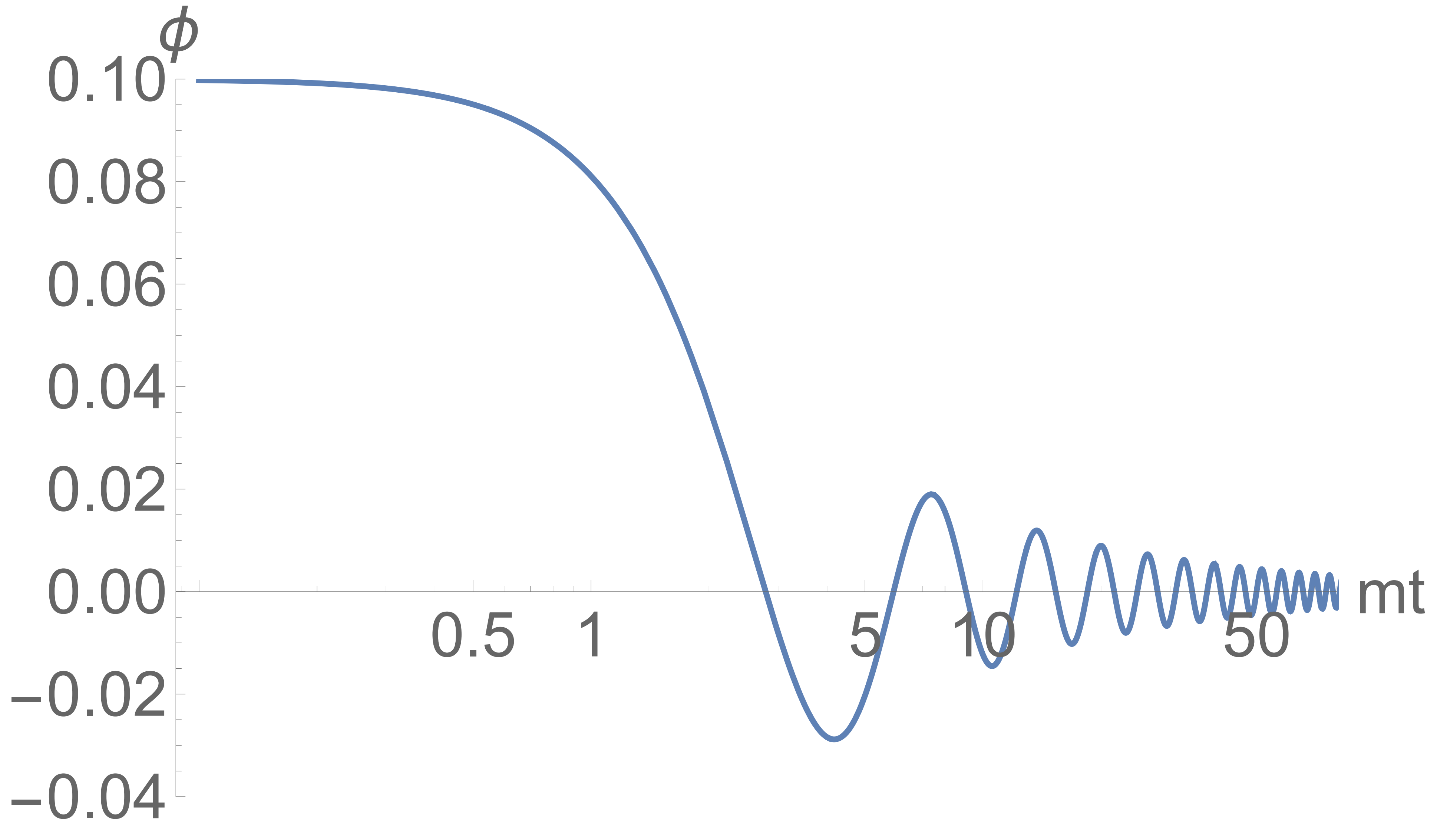

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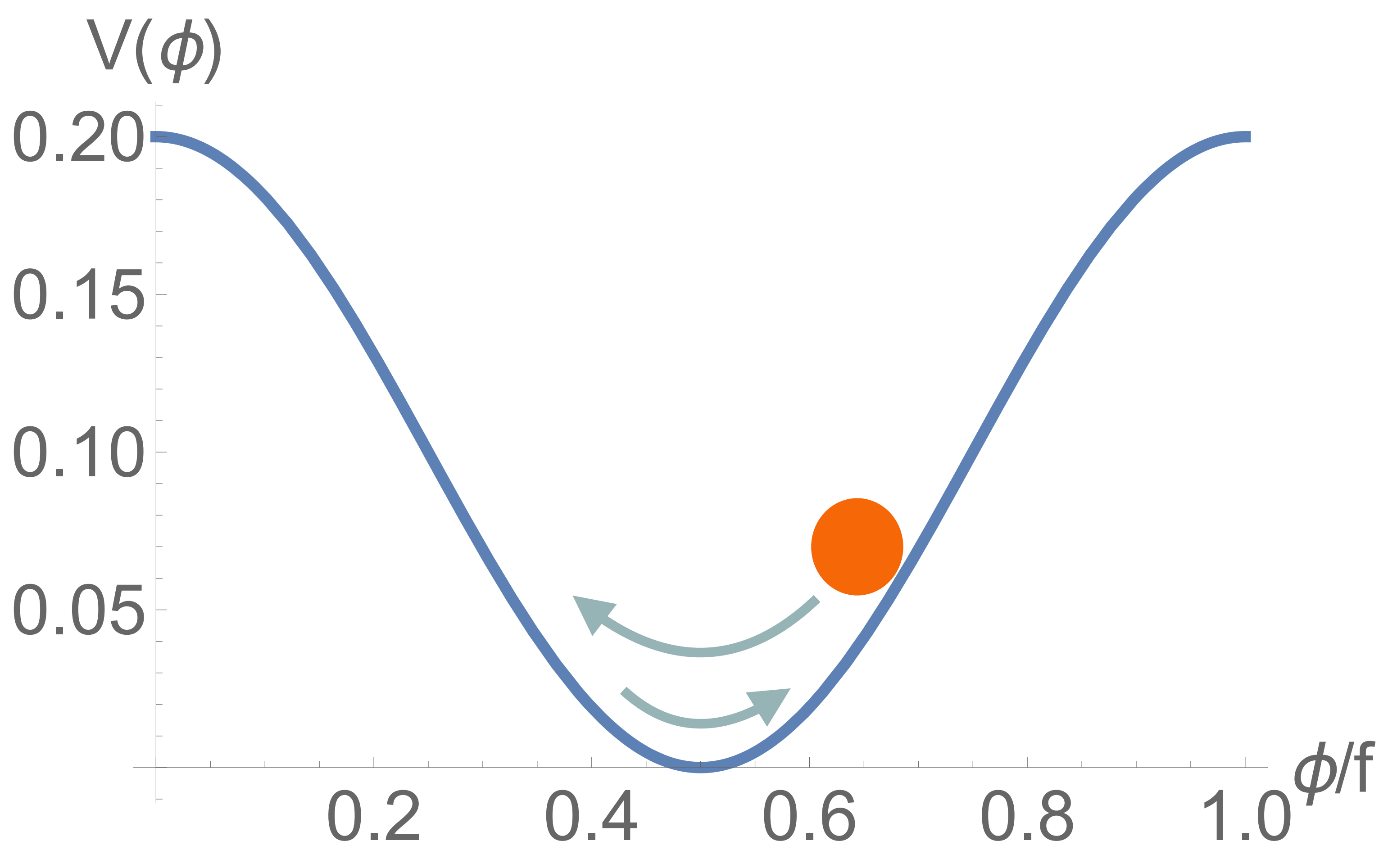

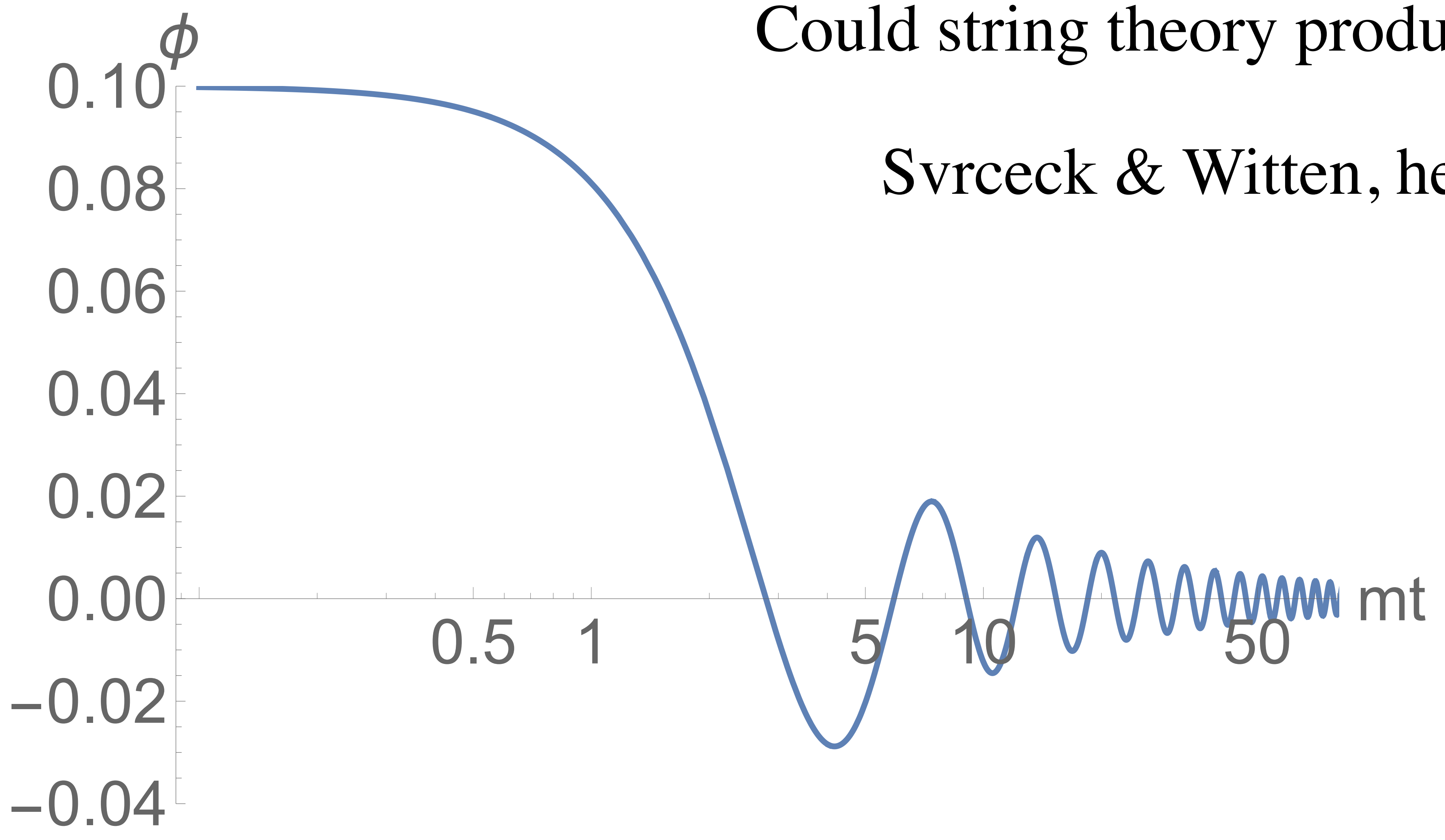

Could string theory produce such states?

Svrceck & Witten, hep-th/0605206

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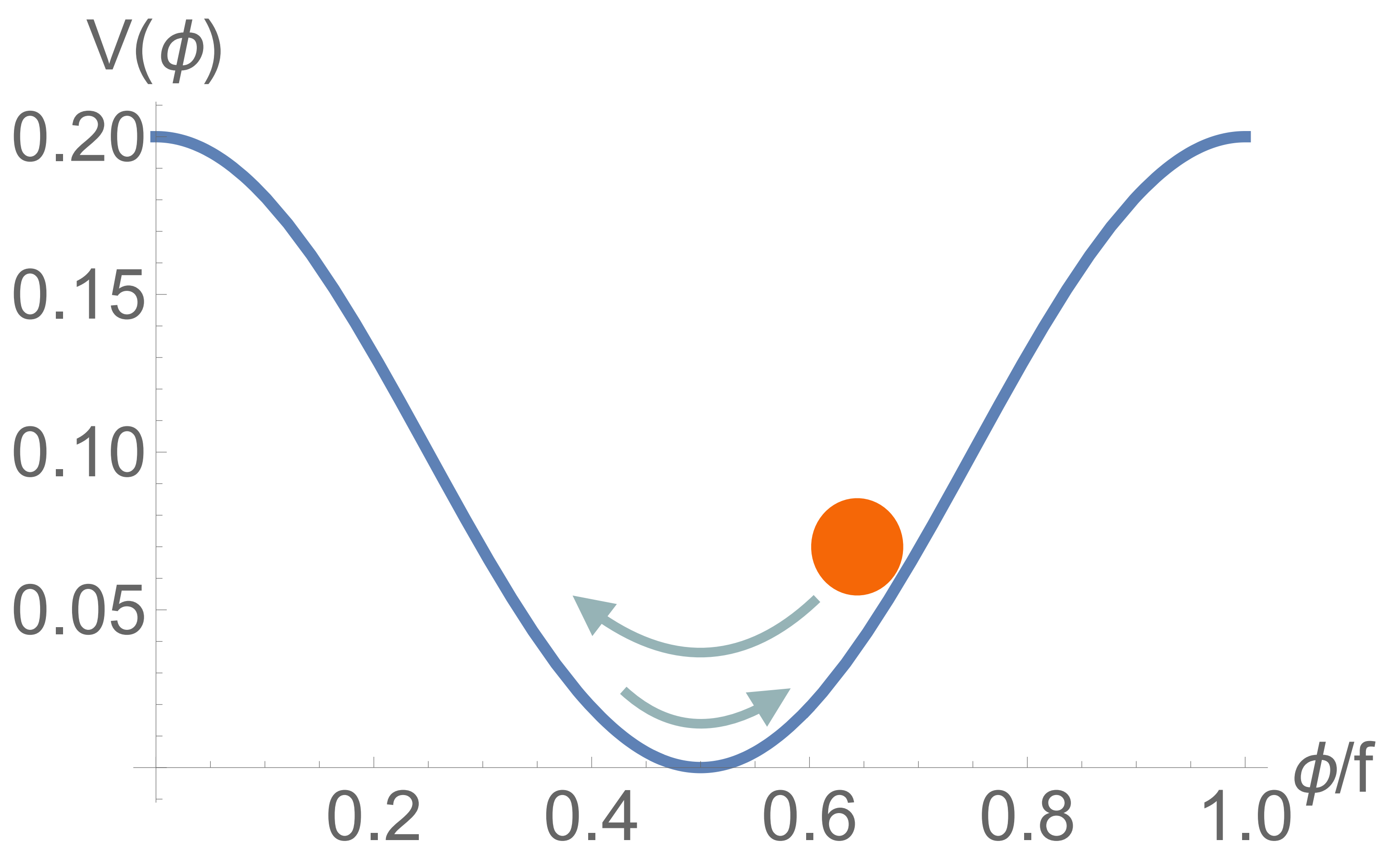
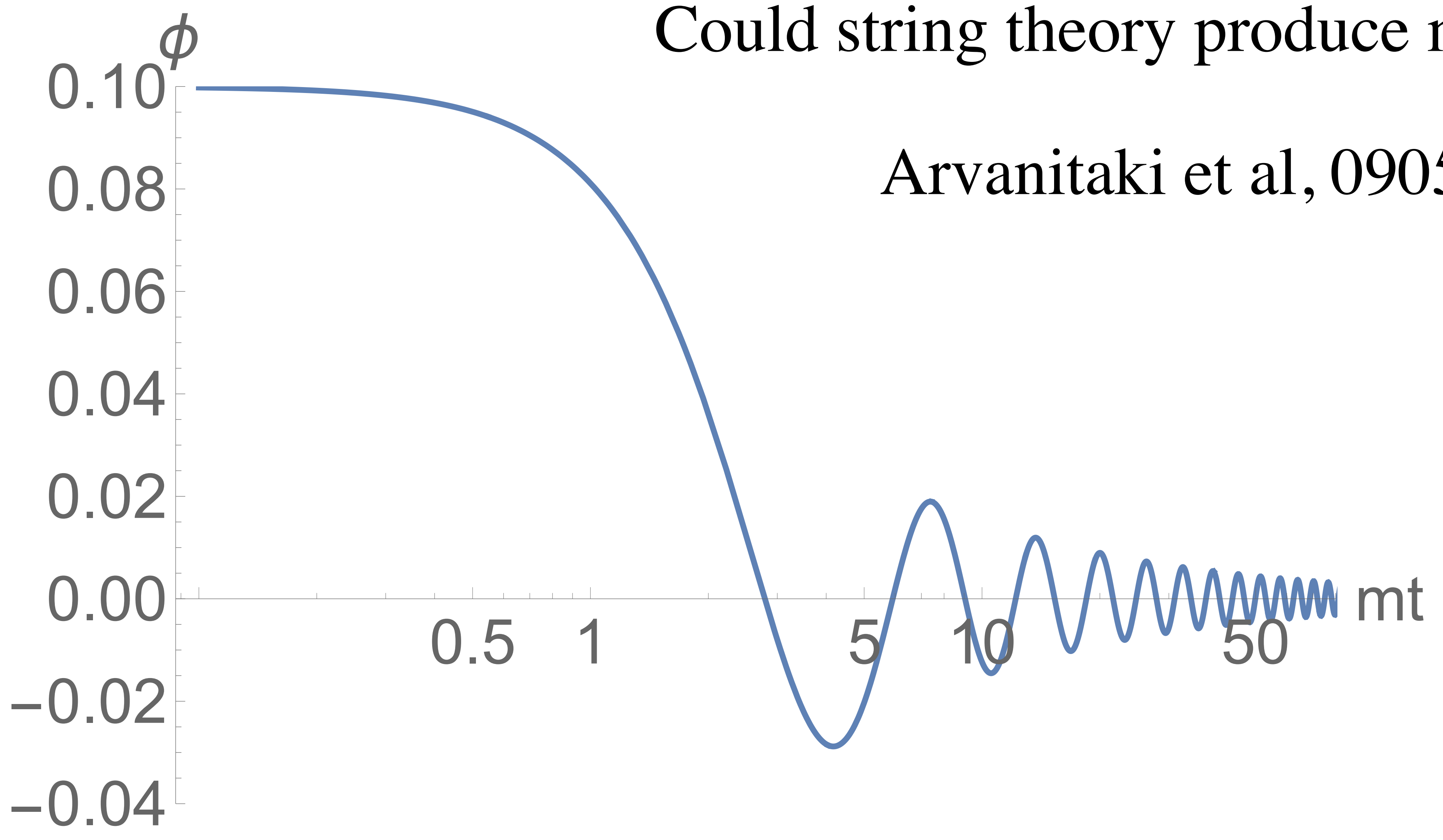
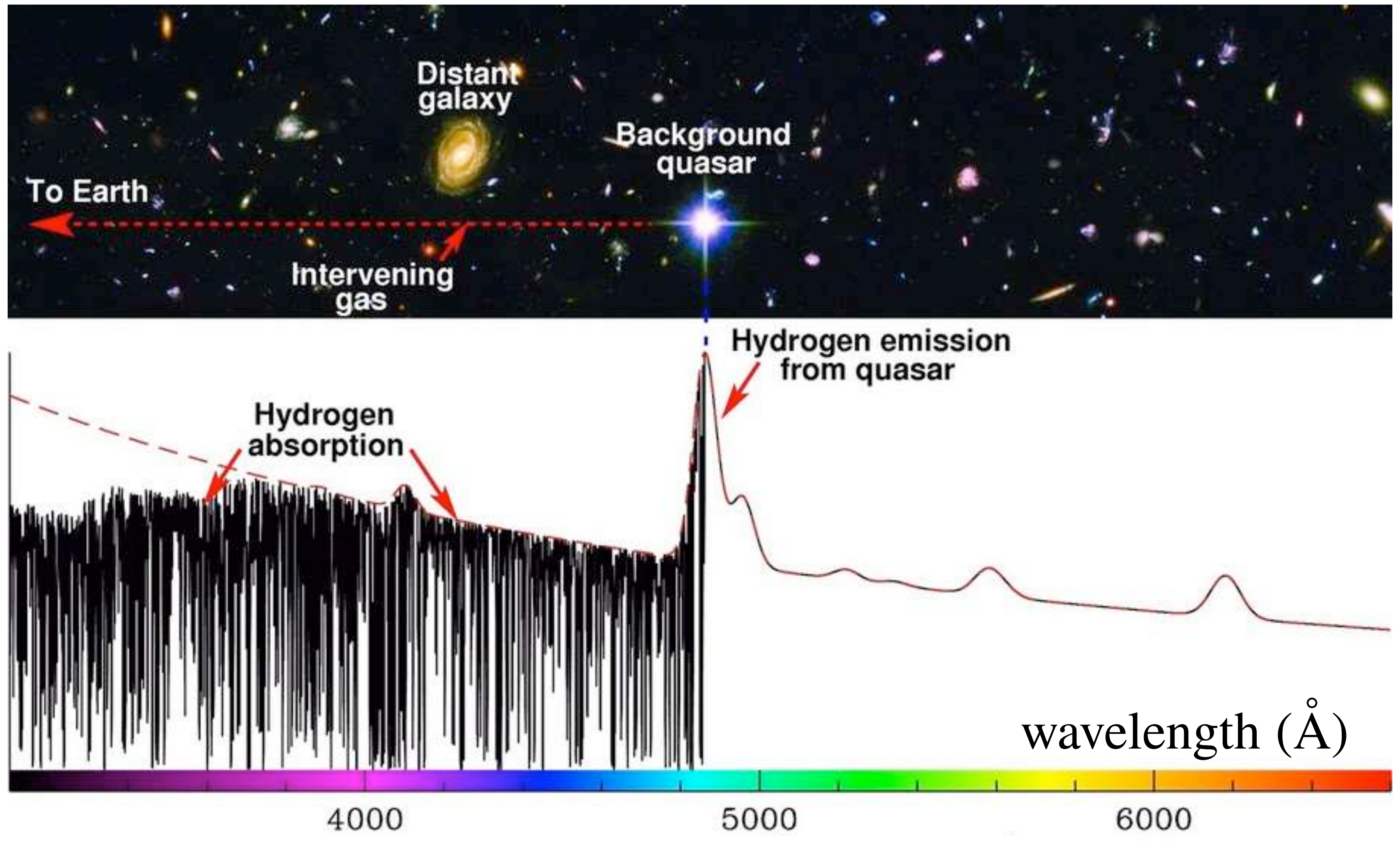




Could string theory produce many such states?

Arvanitaki et al, 0905.4720

On scales smaller than the de Broglie wavelength, **ULDM is different** than massive particle DM.



self-gravitating perturbation:

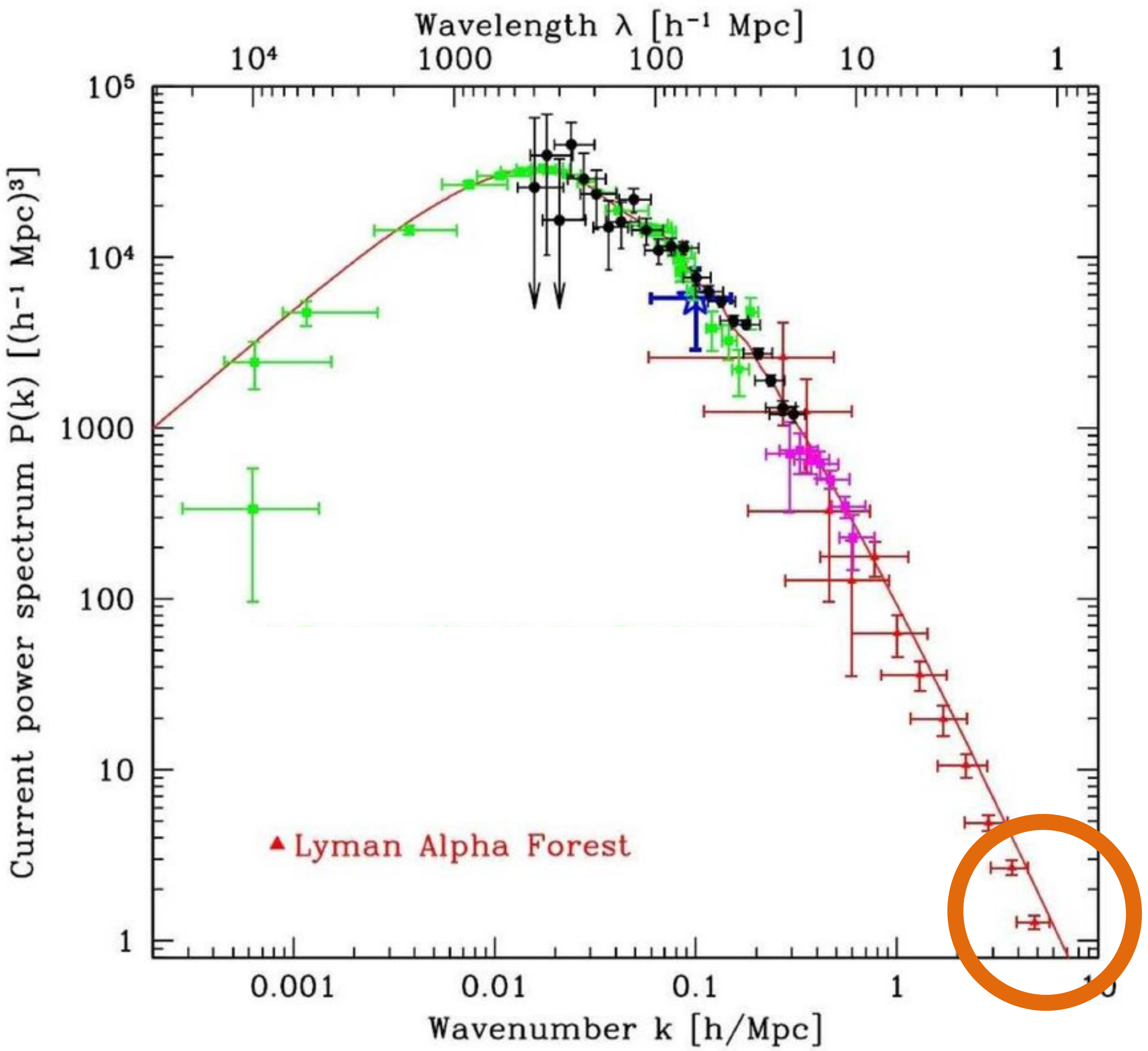
$$v^2 = \frac{GM}{R} = \frac{4\pi}{3} G\delta\rho \left(\frac{\lambda_{\rm dB}}{2}\right)^2$$

$$\frac{\lambda_{\rm dB}}{a} = \frac{2\pi}{amv}$$

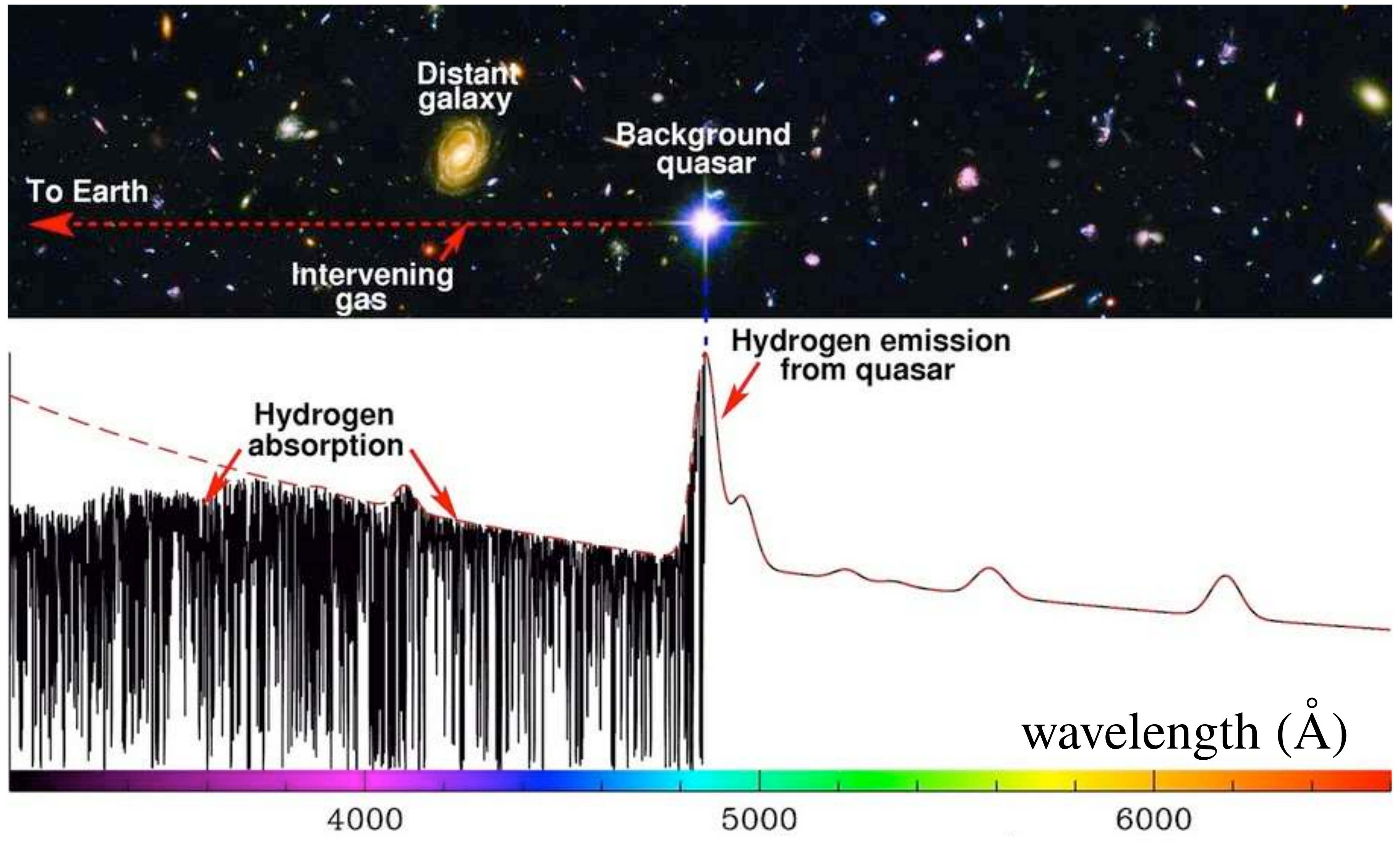
$$\approx 6 \left(\frac{10^{-22}\text{eV}}{m}\right)^{\frac{1}{2}} \left(\frac{10^{-5}}{\delta\rho/\rho}\right)^{\frac{1}{4}} \left(\frac{1+z}{10^3}\right)^{\frac{1}{4}} \text{Mpc}$$

$$\boxed{m \gtrsim 10^{-21}\ \text{eV}}$$

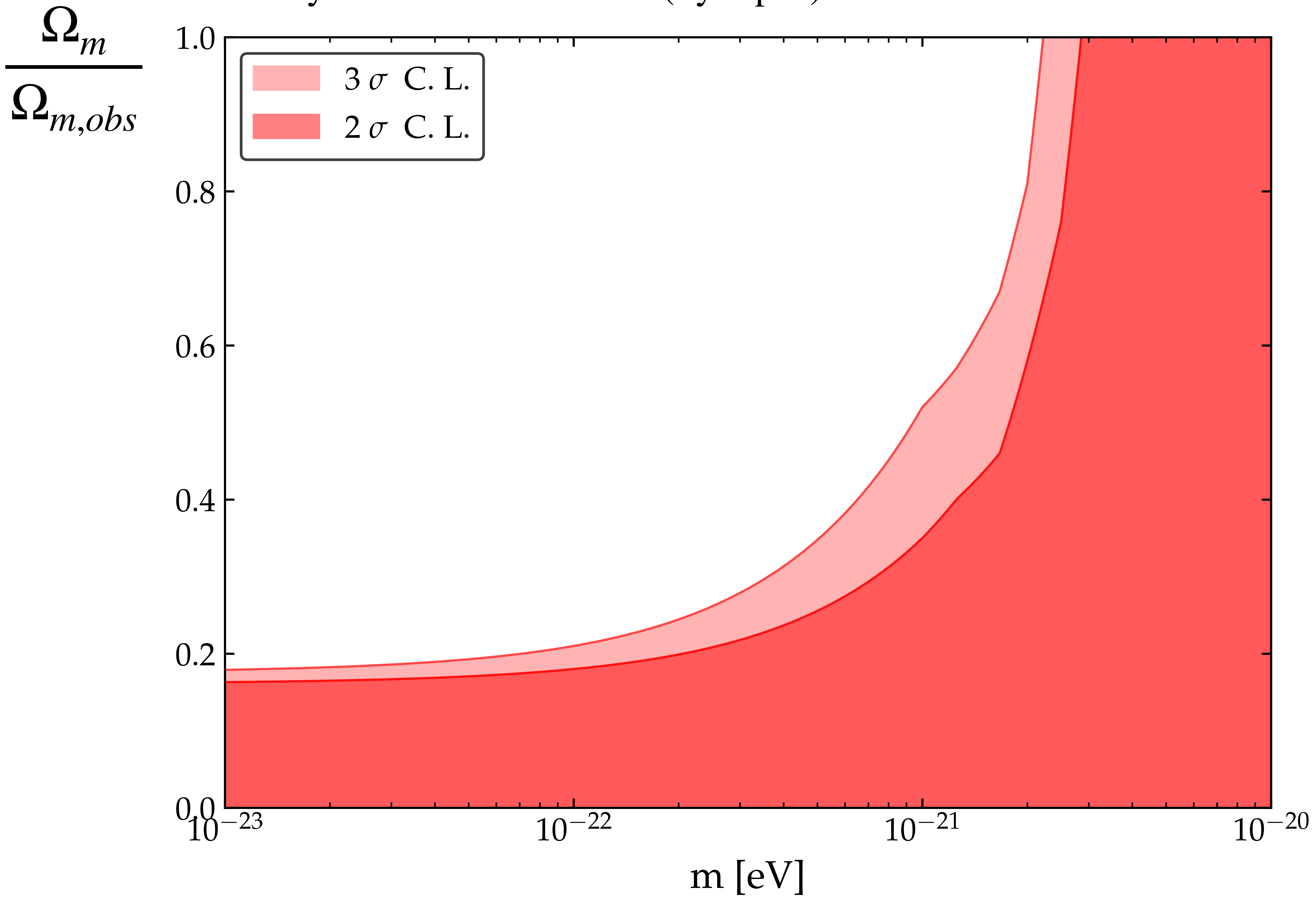
Armengaud et al 2017



On scales smaller than the de Broglie wavelength, **ULDM is different** than massive particle DM.



Kobayashi et al 1708.00015 (Ly-alpha)



See also:
Hlozek, Marsh, Grin 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)

On scales smaller than the de Broglie wavelength, **ULDM is "fuzzy"**

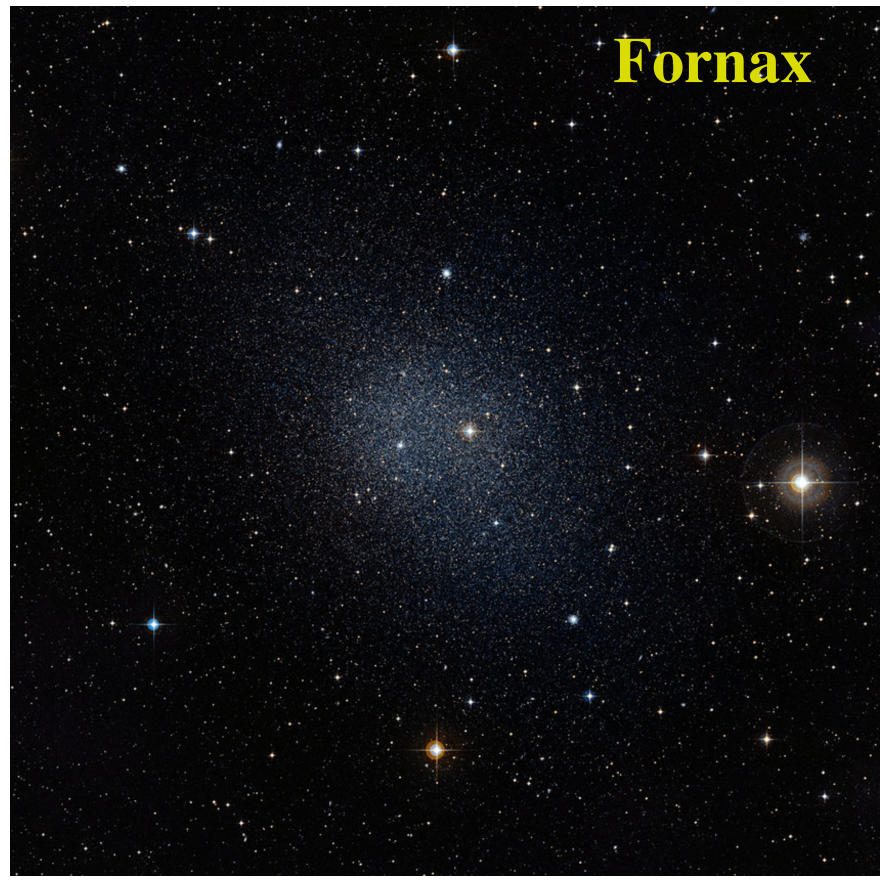
W. Hu, R. Barkana, and A. Gruzinov, Cold and Fuzzy Dark Matter, Phys. Rev. Lett. **85**, 1158 (2000).

$$\lambda_{\mathrm{dB}} \sim \frac{2\pi}{mv}$$

$$v^2 \sim \frac{GM}{R}$$

$$R \sim \lambda_{\mathrm{dB}} \quad \Rightarrow \quad \boxed{MR \lesssim \frac{4\pi^2}{Gm^2}}$$

$$\left(\frac{M}{3\times 10^9\ \mathrm{M}_\odot}\right)\left(\frac{R}{1\ \mathrm{kpc}}\right) \lesssim \left(\frac{10^{-22}\ \mathrm{eV}}{m}\right)^2$$



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[1] W. Hu, R. Barkana, and A. Gruzinov, Cold and Fuzzy Dark Matter, Phys. Rev. Lett. **85**, 1158 (2000).

[2] A. Arbey, J. Lesgourgues, and P. Salati, Quintessential haloes around galaxies, Phys. Rev. D **64**, 123528 (2001).

[3] J. Lesgourgues, A. Arbey, and P. Salati, A light scalar field at the origin of galaxy rotation curves, New Astron. Rev. **46**, 791 (2002).

[4] P.-H. Chavanis, Mass-radius relation of Newtonian self-gravitating Bose-Einstein condensates with short-range interactions: I. Analytical results, Phys. Rev. D **84**, 043531 (2011).

[5] P. H. Chavanis and L. Delfini, Mass-radius relation of Newtonian self-gravitating Bose-Einstein condensates with short-range interactions: II. Numerical results, Phys. Rev. D **84**, 043532 (2011).

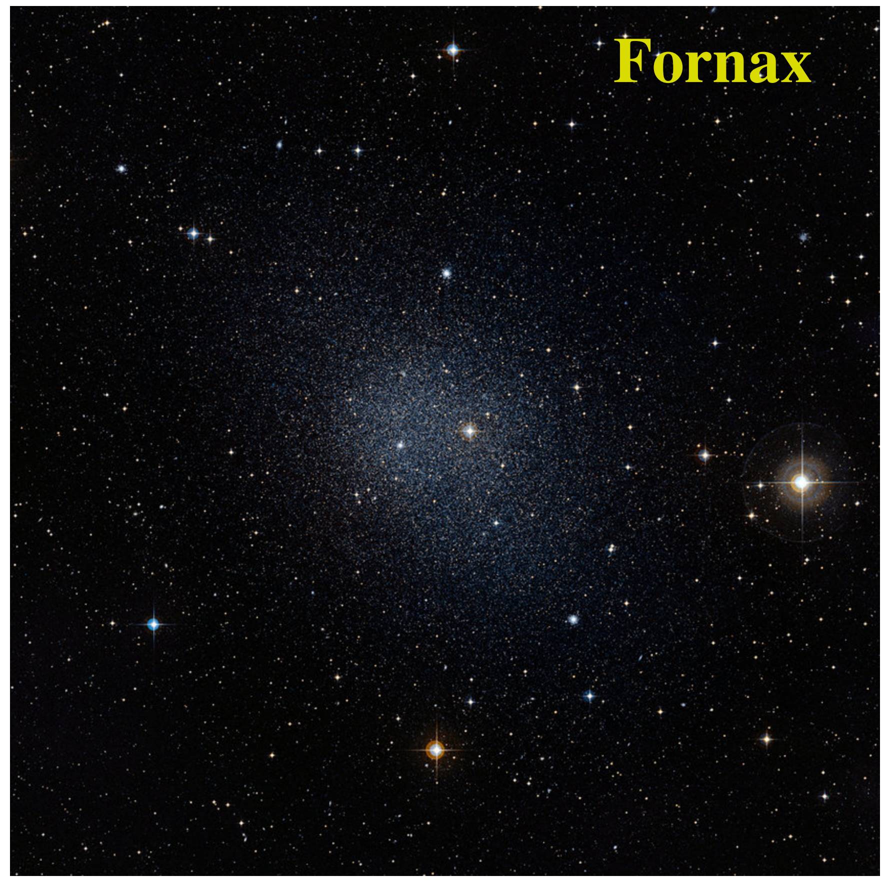
[6] H.-Y. Schive, T. Chiueh, and T. Broadhurst, Cosmic structure as the quantum interference of a coherent dark wave, Nat. Phys. **10**, 496 (2014).

[7] H.-Y. Schive, M.-H. Liao, T.-P. Woo, S.-K. Wong, T. Chiueh, T. Broadhurst, and W. Y. P. Hwang, Understanding the Core-Halo Relation of Quantum Wave Dark Matter from 3D Simulations, Phys. Rev. Lett. **113**, 261302 (2014).

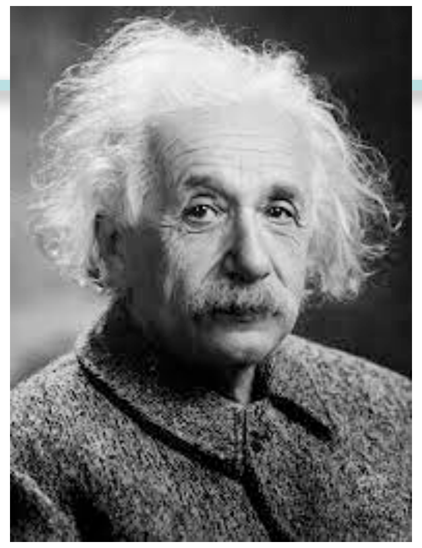
[8] D. J. E. Marsh and A.-R. Pop, Axion dark matter, solitons and the cusp-core problem, Mon. Not. R. Astron. Soc. **451**, 2479 (2015).

[9] S.-R. Chen, H.-Y. Schive, and T. Chiueh, Jeans analysis for Dwarf Spheroidal Galaxies in wave dark matter, Mon. Not. R. Astron. Soc. **468**, 1338 (2017).

It was suggested that Milky Way dwarf satellite galaxies may point to $m \sim 10^{-22}$ eV



Free scalar field $\phi(x,t)$



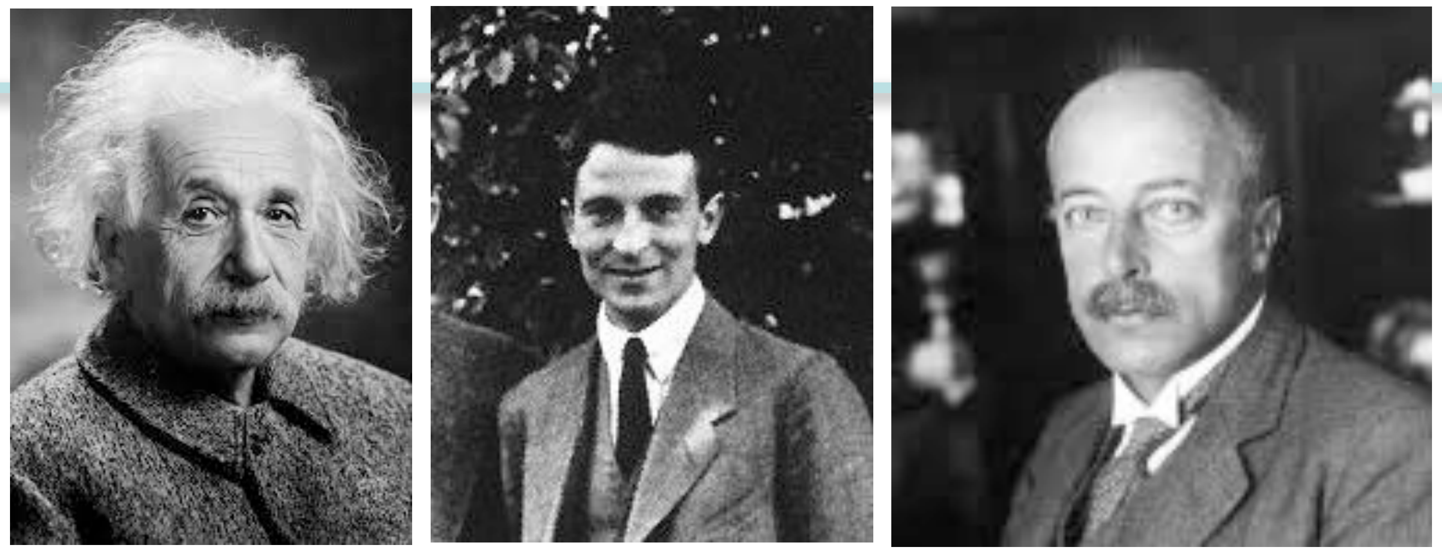
$$\frac{1}{\sqrt{-g}}\frac{\partial}{\partial x^\mu}\left(\sqrt{-g}\,g^{\mu\nu}\frac{\partial\phi}{\partial x^\nu}\right)+m^2\phi=0$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R=8\pi G T_{\mu\nu}$$

Einstein-Klein-Gordon equations

Nonrelativistic limit

Free scalar field $\phi(x,t) = \frac{1}{\sqrt{2m}} e^{-imt} \psi(x,t) + cc$



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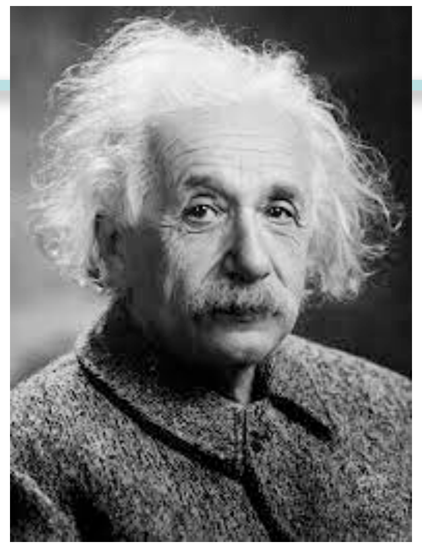

$$i\partial_t \psi = -\frac{1}{2m}\nabla^2 \psi + m\Phi\psi$$

$$\nabla^2 \Phi = 4\pi G |\psi|^2$$

Schrödinger-Poisson equations

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Einstein-Klein-Gordon equations

```
In[•]:= ημν = {{1, 0, 0, 0}, {0, -1, 0, 0}, {0, 0, -1, 0}, {0, 0, 0, -1}};
xμ = {t, x, y, z};
```

$$\texttt{gμνUpper} = \begin{pmatrix} \frac{1}{1+2\,\alpha GR\,\Phi[t,x,y,z]} & 0 & 0 & 0 \\ 0 & \frac{-1}{a[t]^2\,(1-2\,\alpha GR\,\Phi[t,x,y,z])} & 0 & 0 \\ 0 & 0 & \frac{-1}{a[t]^2\,(1-2\,\alpha GR\,\Phi[t,x,y,z])} & 0 \\ 0 & 0 & 0 & \frac{-1}{a[t]^2\,(1-2\,\alpha GR\,\Phi[t,x,y,z])} \end{pmatrix};$$

$$\texttt{gμνLower} = \begin{pmatrix} 1+2\,\alpha GR\,\Phi[t,x,y,z] & 0 & 0 & 0 \\ 0 & -a[t]^2\,(1-2\,\alpha GR\,\Phi[t,x,y,z]) & 0 & 0 \\ 0 & 0 & -a[t]^2\,(1-2\,\alpha GR\,\Phi[t,x,y,z]) & 0 \\ 0 & 0 & 0 & -a[t]^2\,(1-2\,\alpha GR\,\Phi[t,x,y,z]) \end{pmatrix};$$

```
Dmg = Det[-gμνLower];
```

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$$\nabla^2\Phi = 4\pi G|\psi|^2$$

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Einstein-Klein-Gordon equations

```
In[•]:= ϕ[t, x, y, z] = E^(-I m t)/(Sqrt[2] m) (ψr[t, x, y, z] + I ψi[t, x, y, z]) + E^(I m t)/(Sqrt[2] m) (ψr[t, x, y, z] - I ψi[t, x, y, z]);

EOMϕ = 1/Sqrt[Dmg] Sum[D[Sqrt[Dmg] gμνUpper[[μ, ν]] × D[ϕ[t, x, y, z], xμ[[ν]]], xμ[[μ]]], {μ, 1, 4}, {ν, 1, 4}] + m^2 ϕ[t, x, y, z];

In[•]:= FullSimplify[-m/Sqrt[2] EOMϕNewt /. {Ψ -> Φ}]

Out[•]= 1/a[t]^2 (1 + 2 Φ[t, x, y, z]) (Sin[m t] (ψi^(0,0,0,2)[t, x, y, z] + ψi^(0,0,2,0)[t, x, y, z] + ψi^(0,2,0,0)[t, x, y, z]) +
    Cos[m t] (ψr^(0,0,0,2)[t, x, y, z] + ψr^(0,0,2,0)[t, x, y, z] + ψr^(0,2,0,0)[t, x, y, z])) + ...
```

$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi$$

$$\nabla^2\Phi = 4\pi G|\psi|^2$$

Schrödinger-Poisson equations

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```

adding i x (Sin part) + (Cos part):

$$i\,\partial_t \psi == -\frac{1}{2\,m}\nabla^2\psi + m\,\Phi\,\psi \quad \underbrace{+\frac{1}{2\,m}\partial^2{}_t\,\psi \; - \; 2\,\psi i\,\partial_t\Phi - \frac{2}{m}\partial_t\Phi\,\partial_t\psi r \; + 2\,i\,\partial_t\Phi\left(\psi r - \frac{1}{m}\partial_t\psi i\right) - \frac{1}{m}\Phi\,\nabla^2\psi \; + \;\ldots}_{\text{subleading corrections}}$$

$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi$$

$$\nabla^2\Phi = 4\pi G|\psi|^2$$

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Einstein-Klein-Gordon equations

An aside: Madelung representation

$$\psi = \sqrt{\rho} e^{i\theta} \qquad \nabla \theta = m\mathbf{v}$$

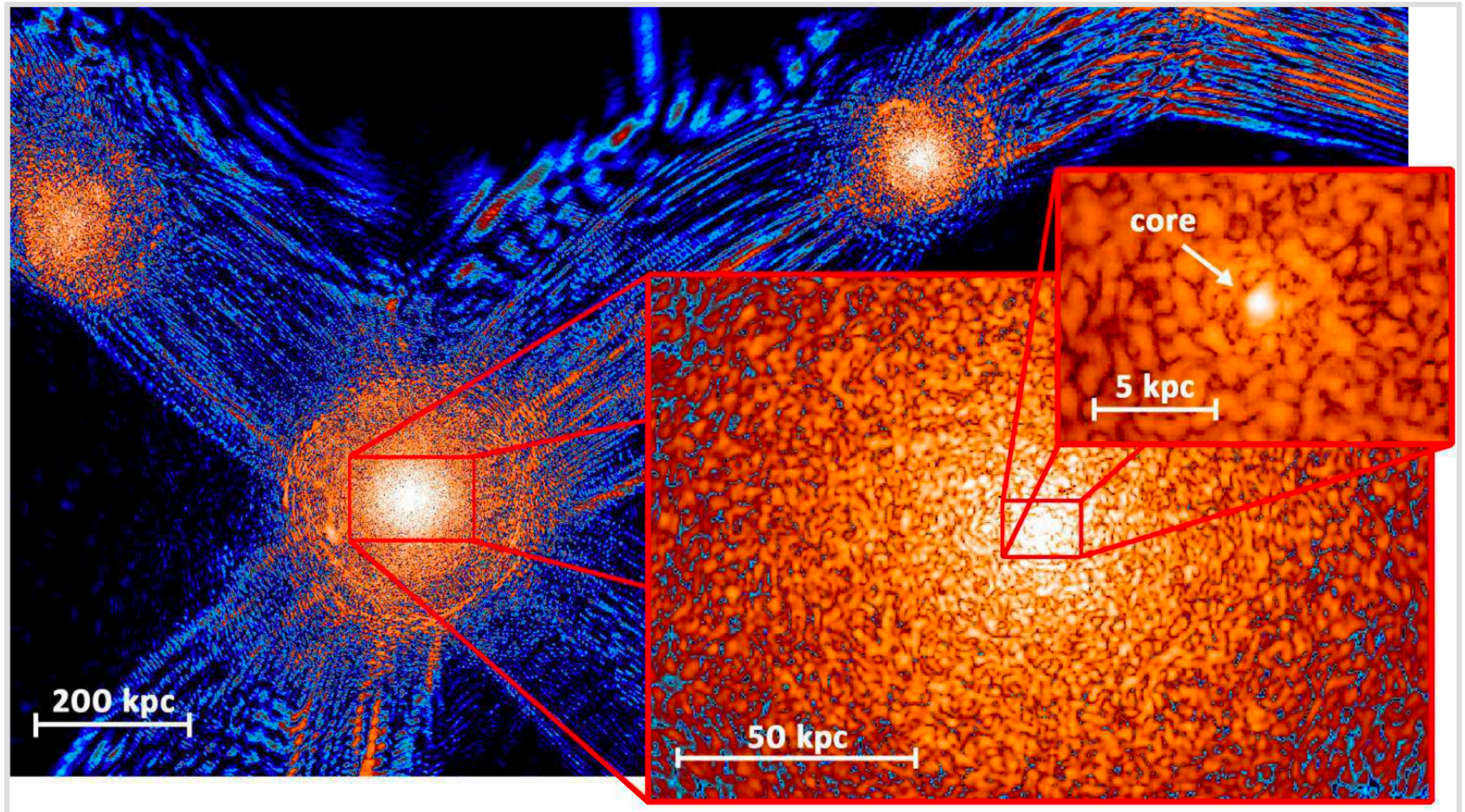
$$i\partial_t \psi = -\frac{1}{2m}\nabla^2 \psi + m\Phi\psi$$

$$\dot{\rho} + \nabla \cdot \left(\rho \mathbf{v}\right) = 0$$

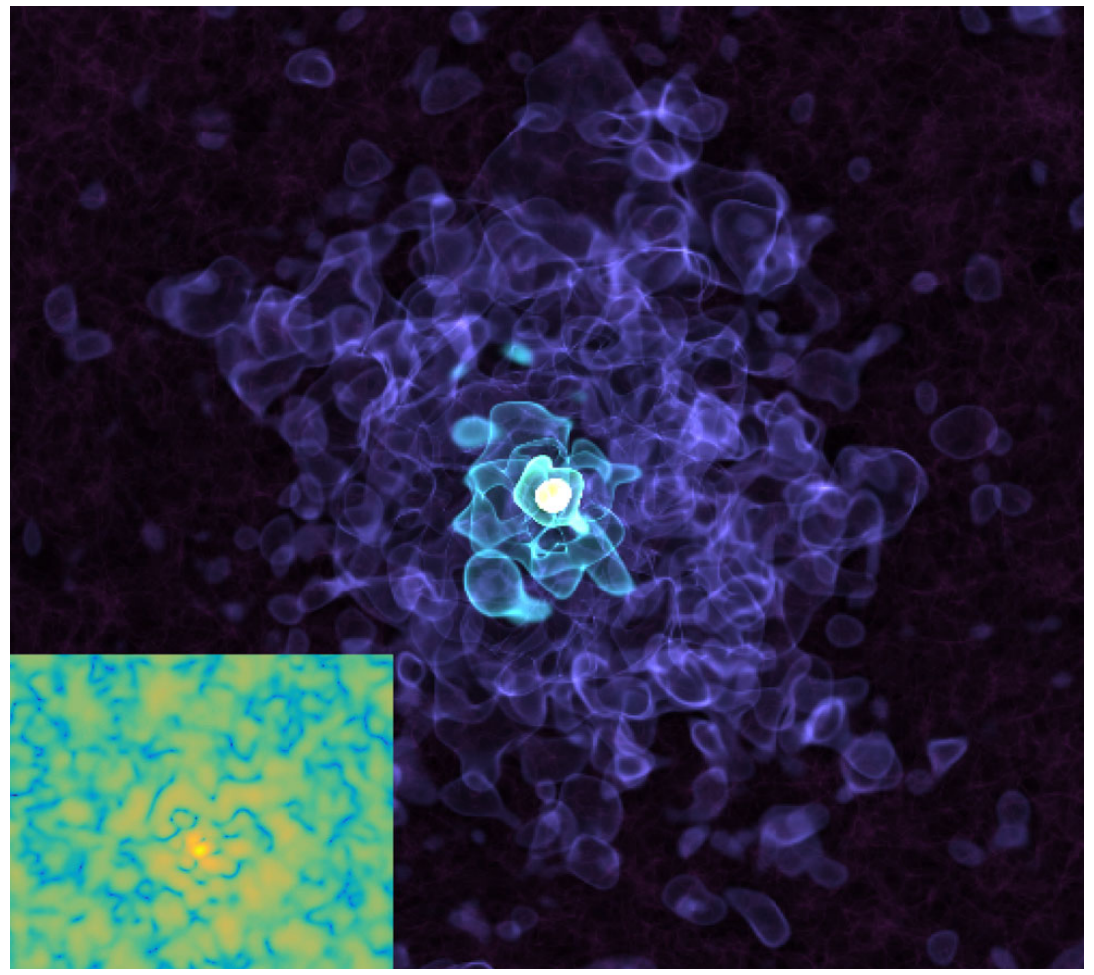
$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla\Phi + \frac{1}{2m^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

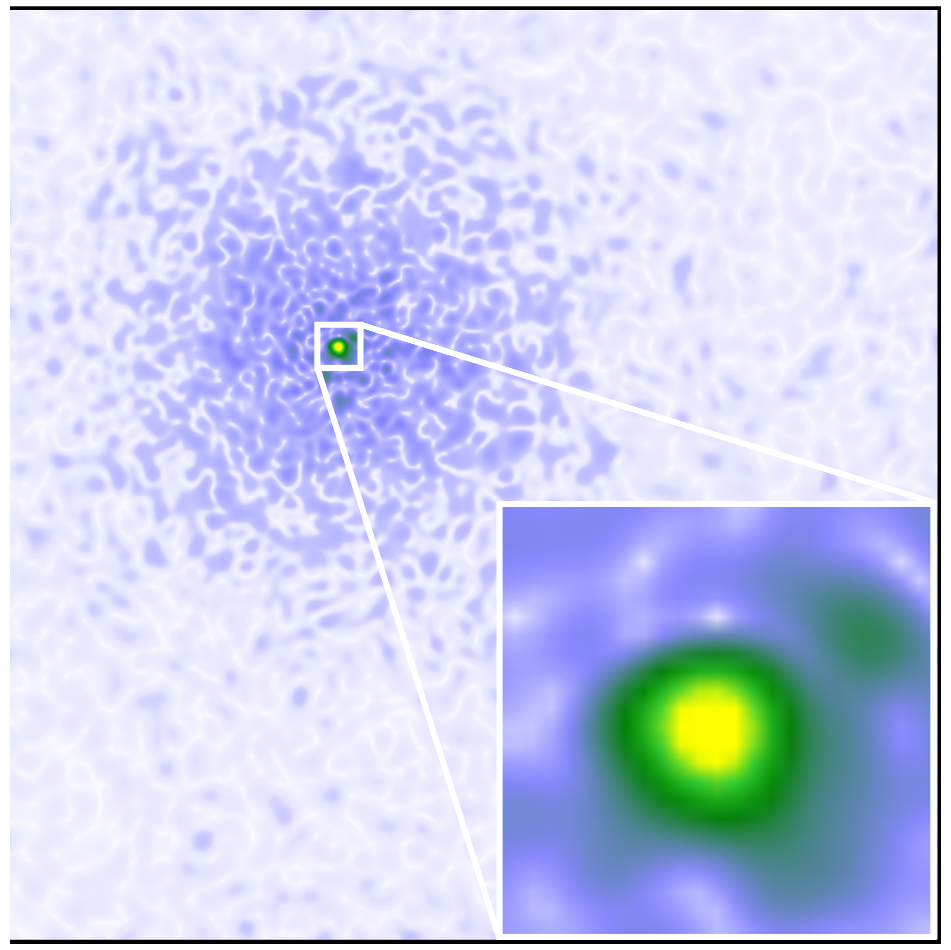
Numerical simulations

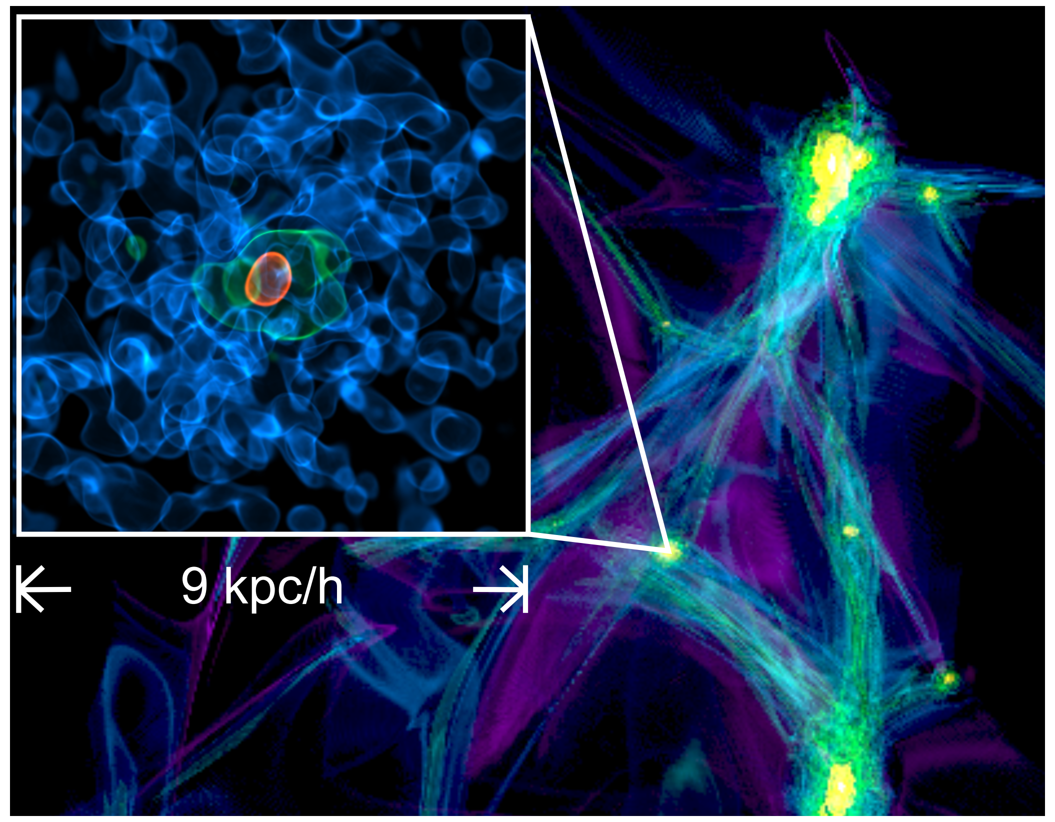
$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi$$
$$\nabla^2\Phi = 4\pi G|\psi|^2$$



Schive et al 2014


Mocz et al 2017


Levkov et al 2018



Veltmaat et al 2018

Inner part of simulated galaxies forms a **core**

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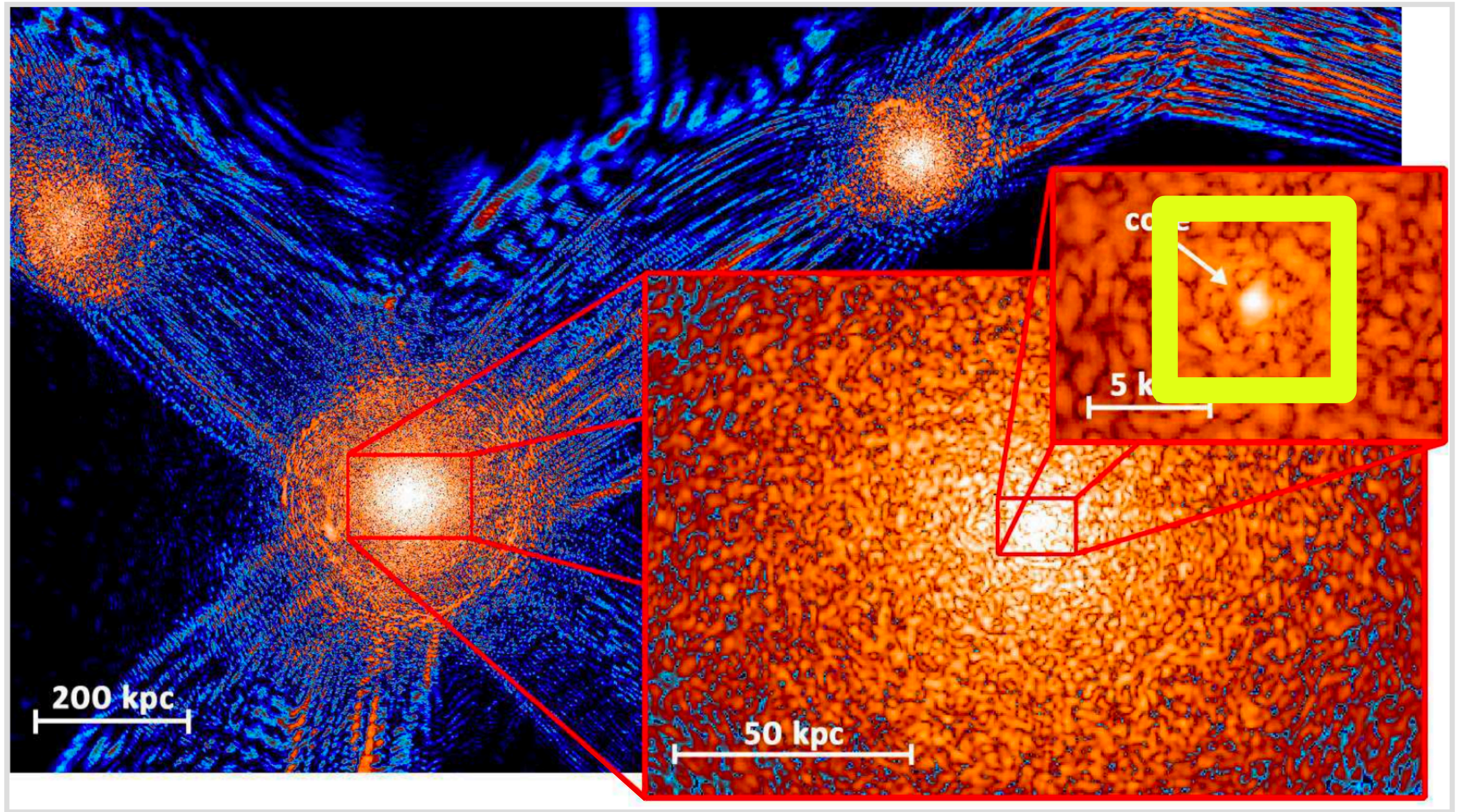
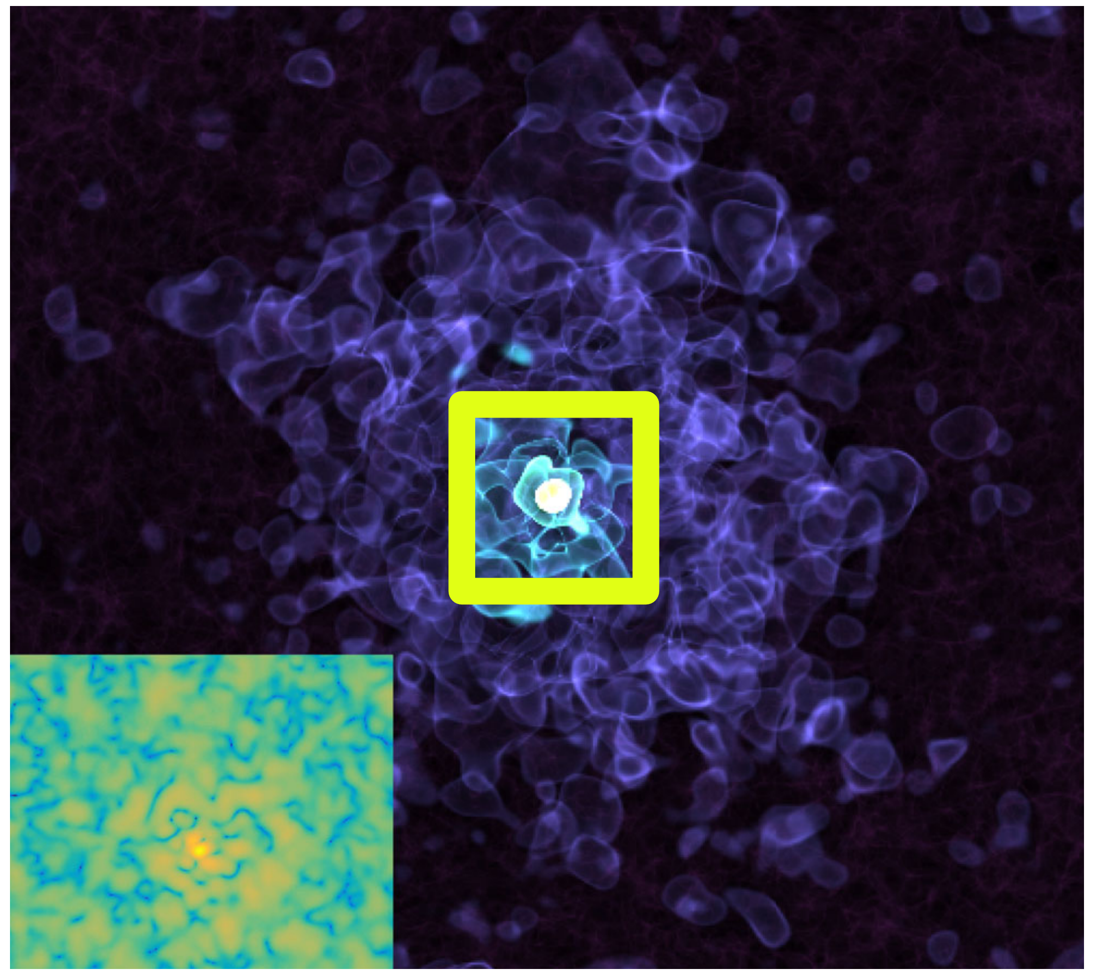
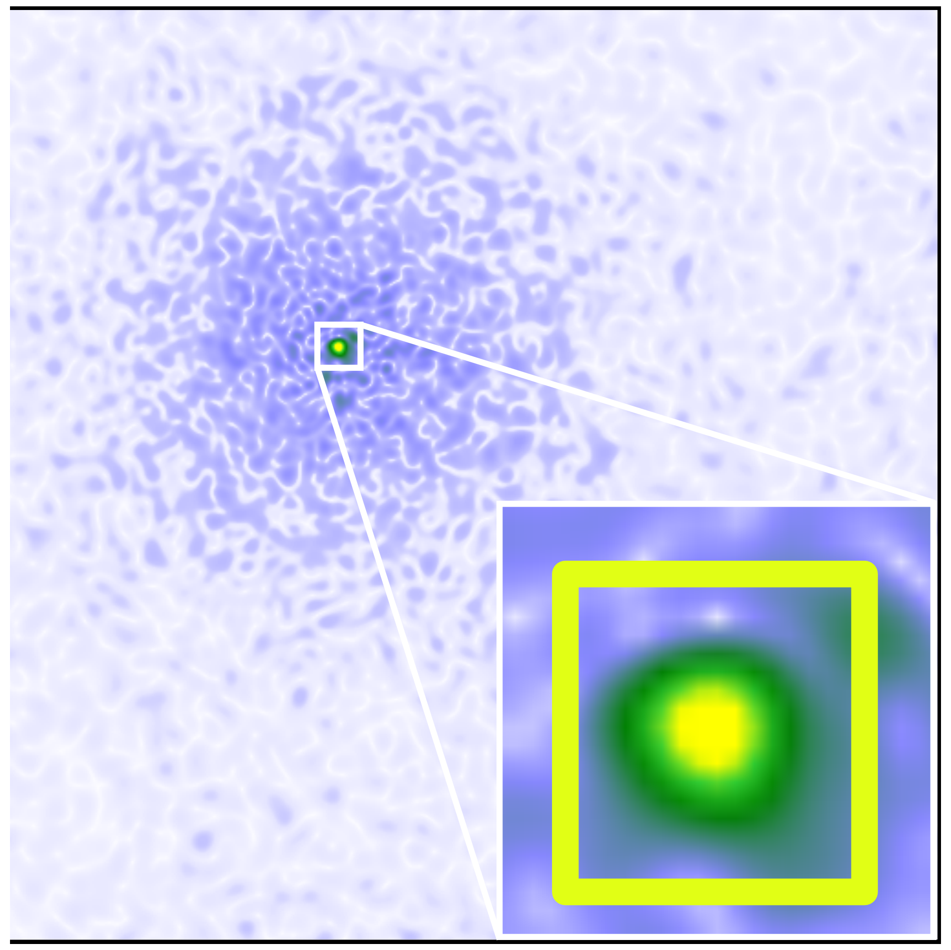
$$\nabla^2\Phi = 4\pi G|\psi|^2$$



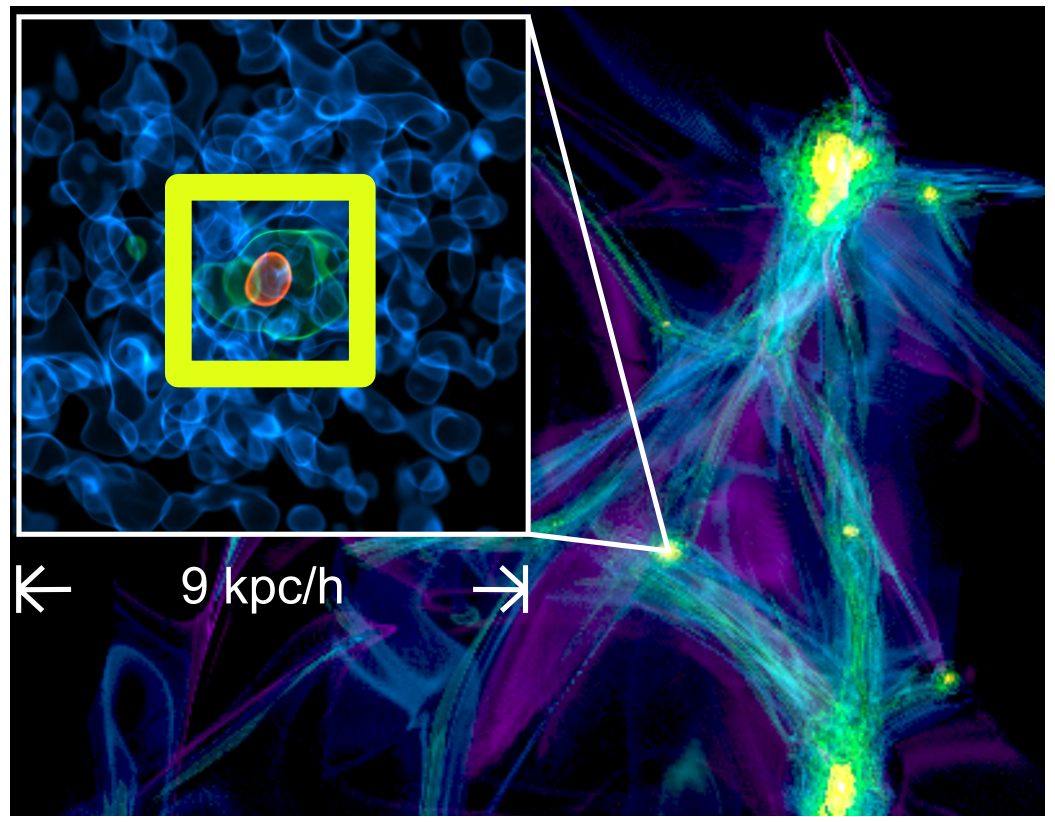
Schive et al 2014



Mocz et al 2017



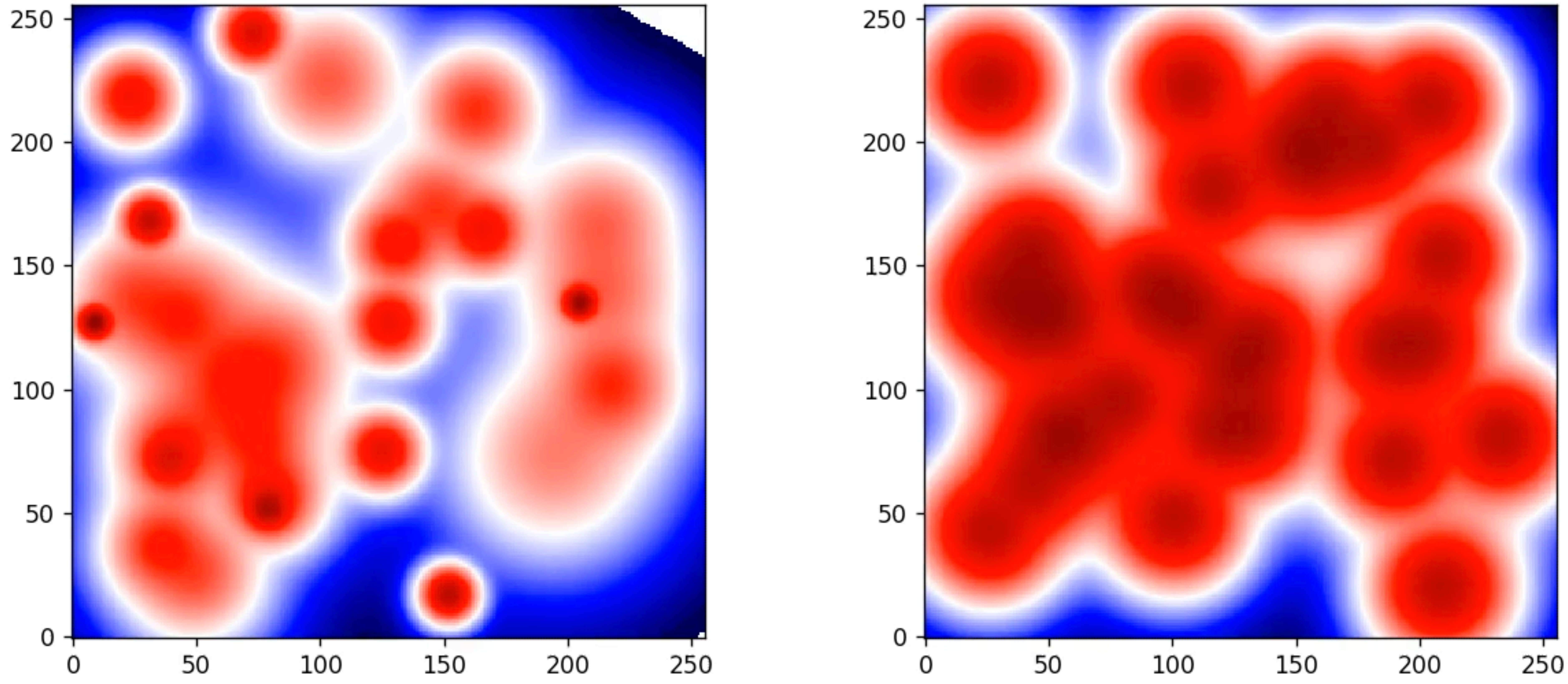
Levkov et al 2018



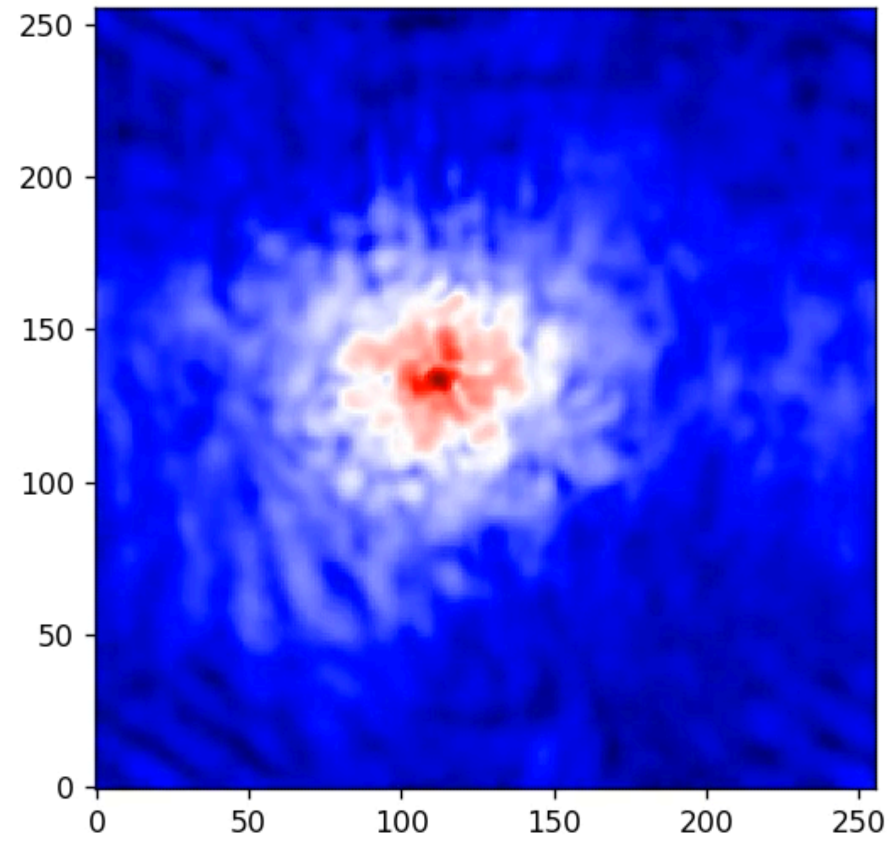
Veltmaat et al 2018

Inner part of simulated galaxies forms a **core**

Simulation: L. Teodori, M. Gorghetto



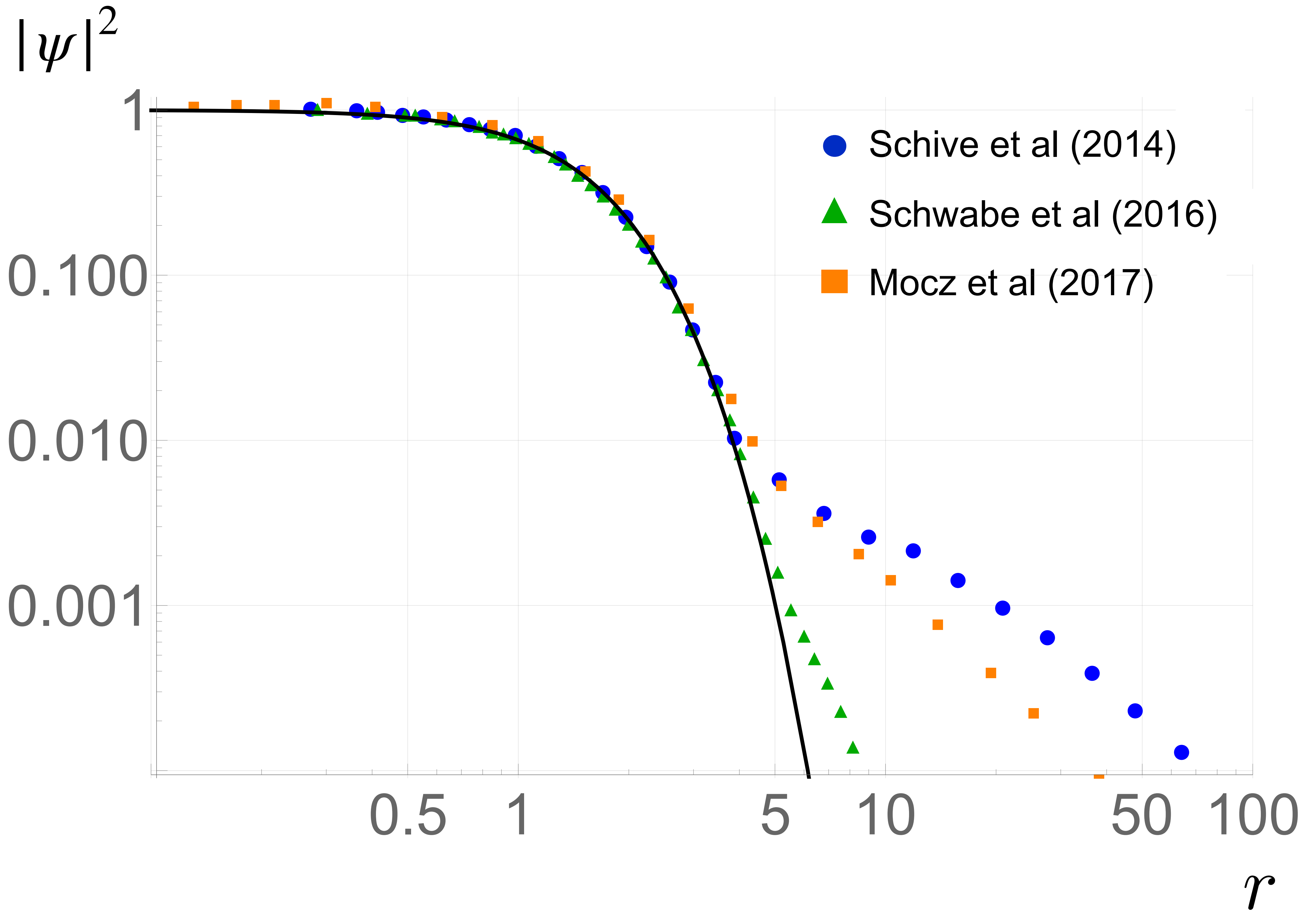
Coherent ground state: $\psi(x,t) = \left(\frac{mM_{pl}}{\sqrt{4\pi}}\right) e^{-i\gamma m t}\chi(r)$



$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi$$
$$\nabla^2\Phi = 4\pi G|\psi|^2$$

$$\partial_r^2\left(r\chi\right) = 2r\left(\Phi - \gamma\right)\chi$$
$$\partial_r^2\left(r\Phi\right) = r\chi^2$$

Numerical simulations find the ground state.



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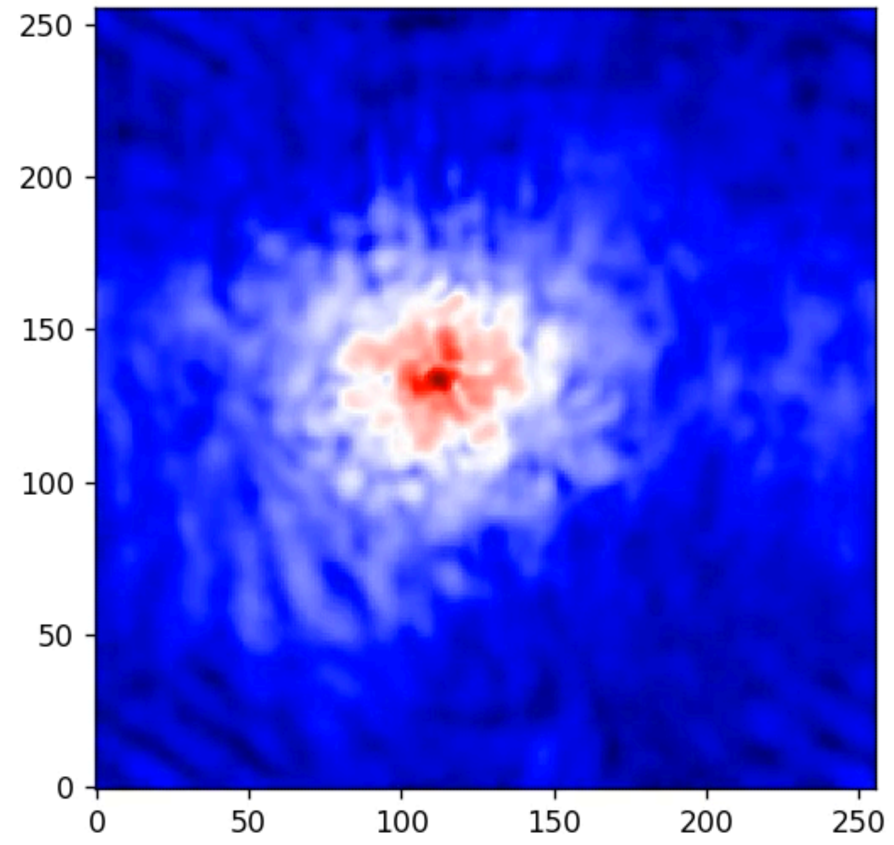

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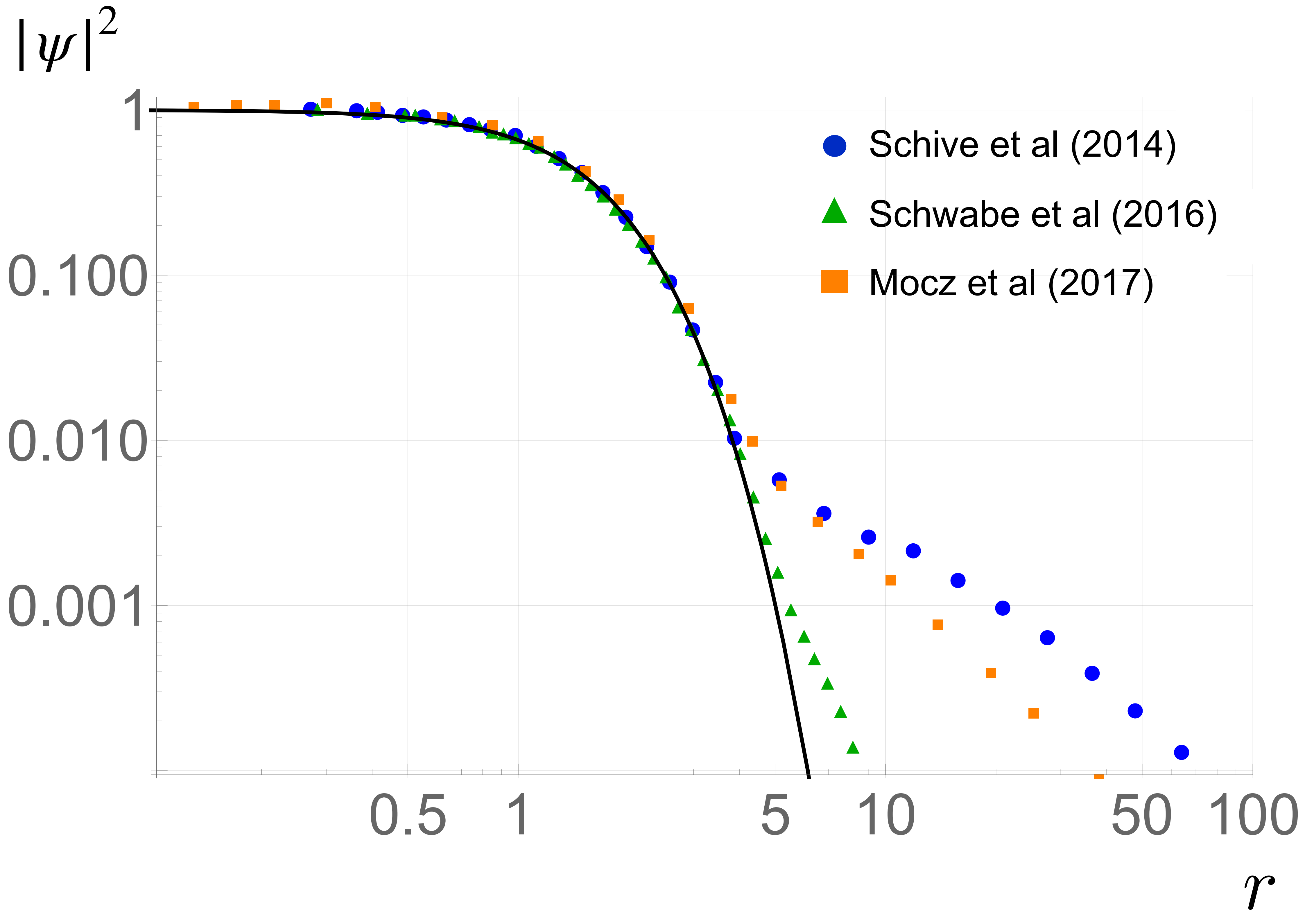
$$\partial_r^2\left(r\Phi\right) = r\chi^2$$

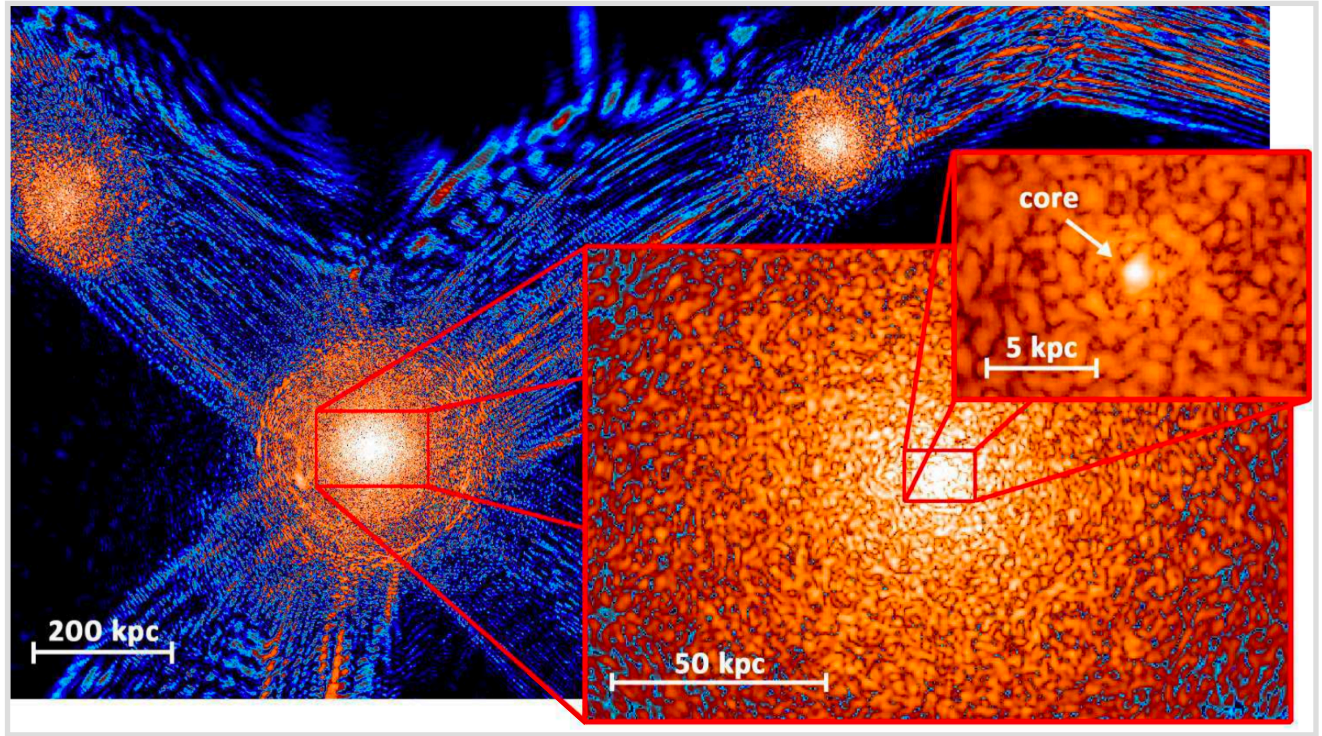
Numerical simulations find the ground state.

This is reminiscent of BEC:
Gross-Pitaevskii with nonlocal interaction:

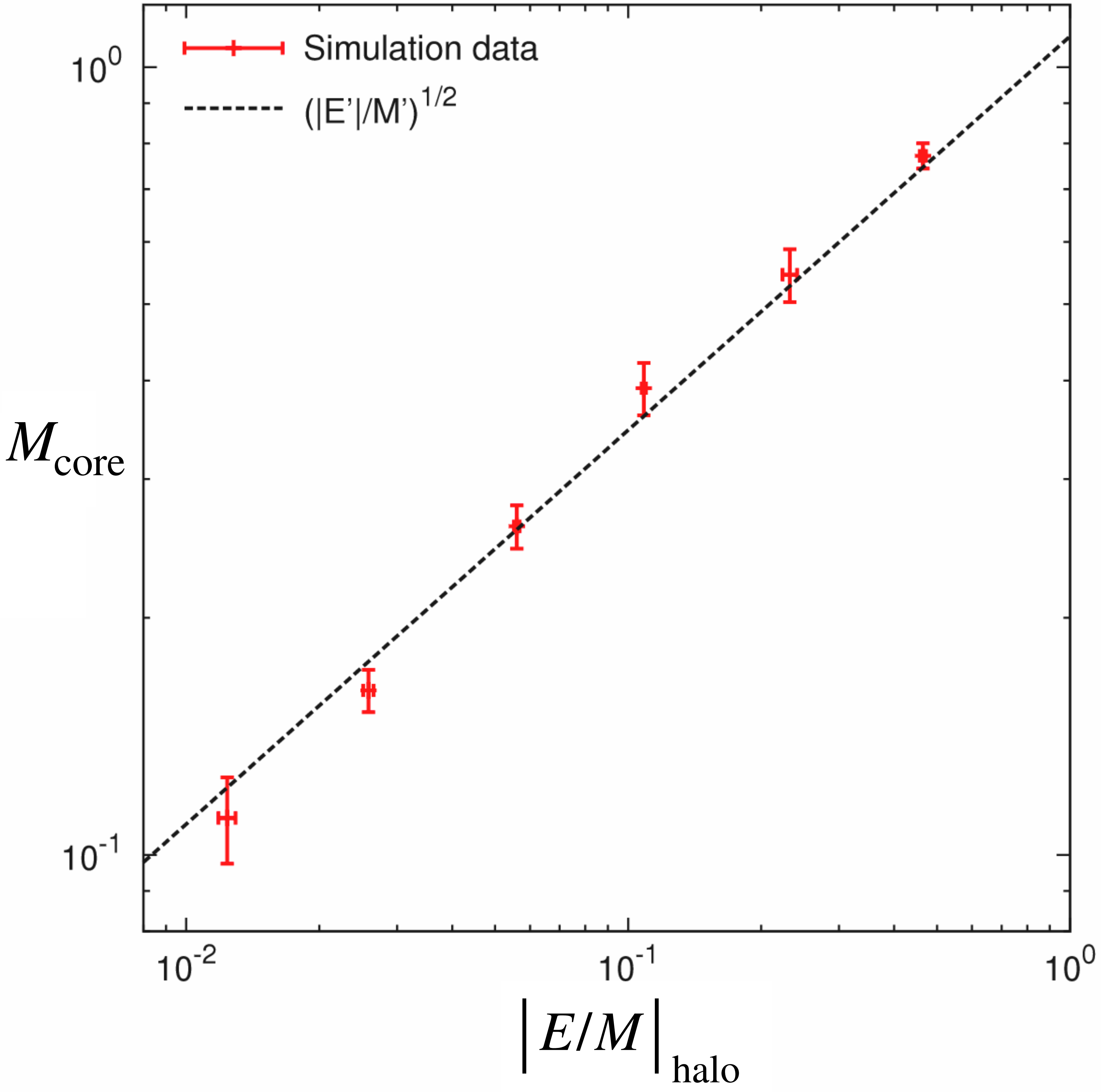
$$i\partial_t\psi(x) = -\left(\frac{1}{2m}\nabla^2 + Gm\int d^3y\frac{|\psi(y)|^2}{|x-y|}\right)\psi(x)$$



Core — halo relation



Schive et al
1406.6586, 1407.7762



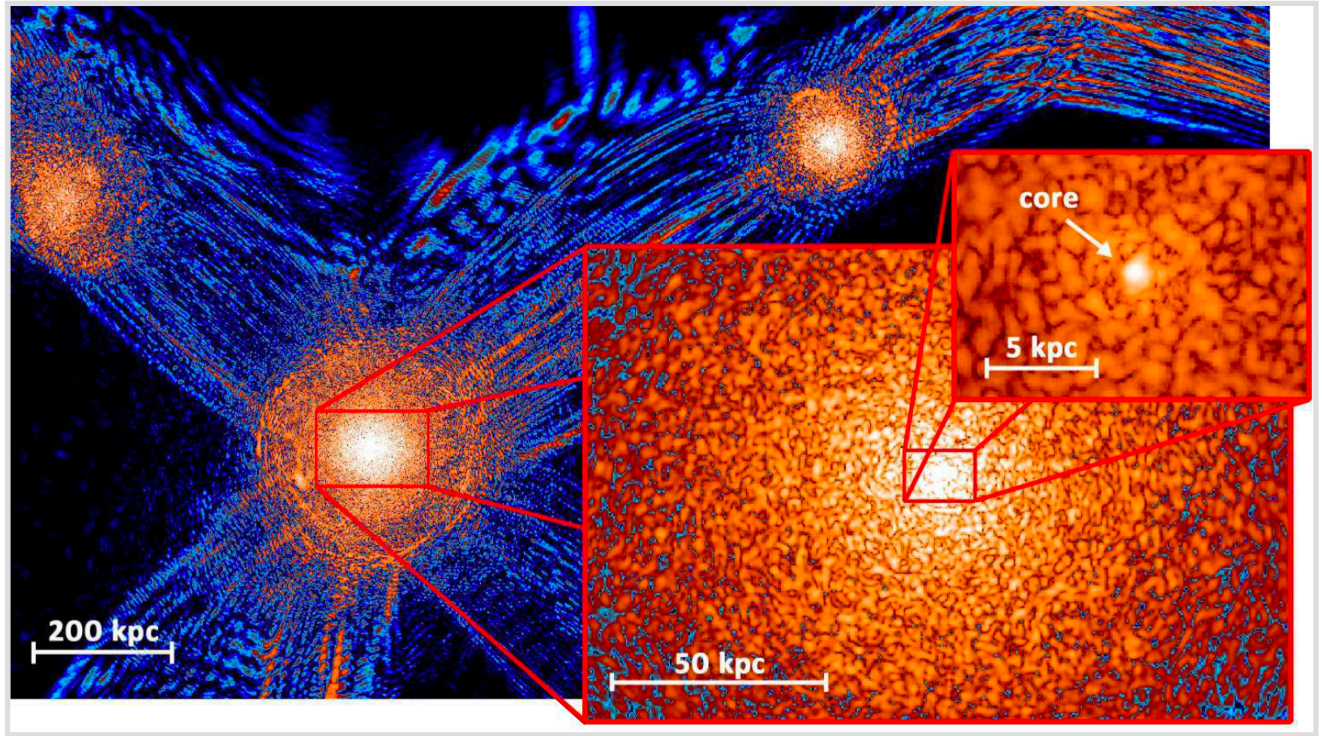
Core — halo relation

Bar, et al 1805.00122

$$\boxed{\left.\frac{E}{M}\right|_{\text{core}} = \left.\frac{E}{M}\right|_{\text{halo}}}$$

$$M = \int d^3x \, |\psi|^2$$

$$E = \int d^3x \left(\frac{|\nabla\psi|^2}{2m^2} + \frac{\Phi|\psi|^2}{2} \right)$$



Schive et al
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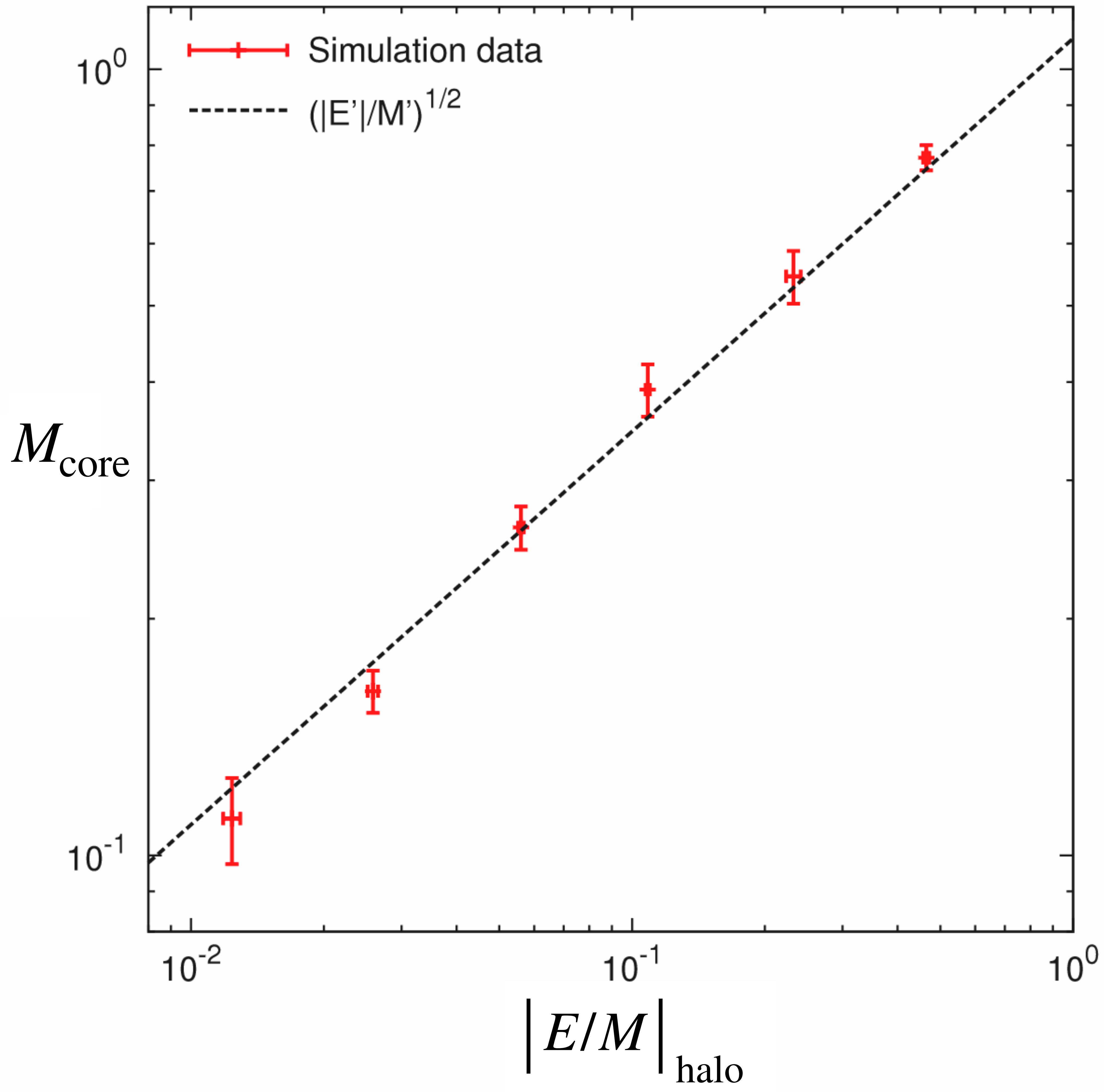

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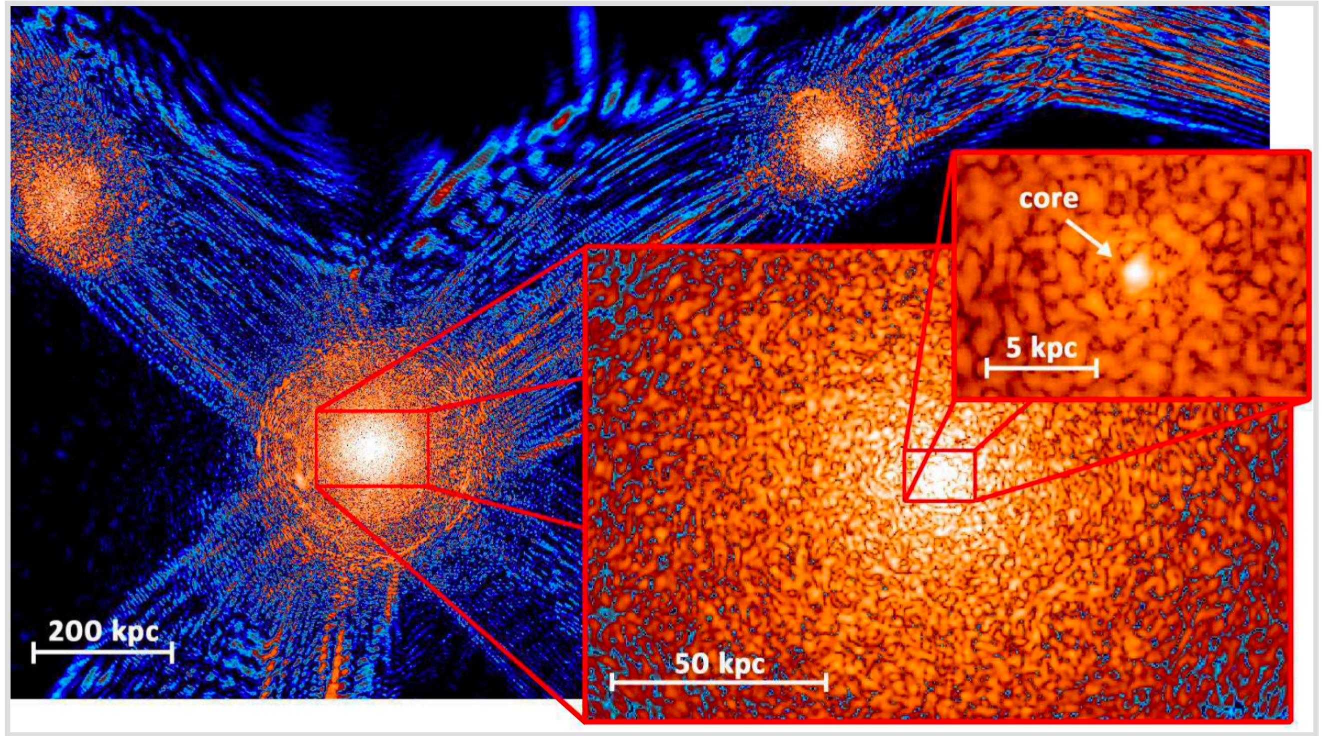
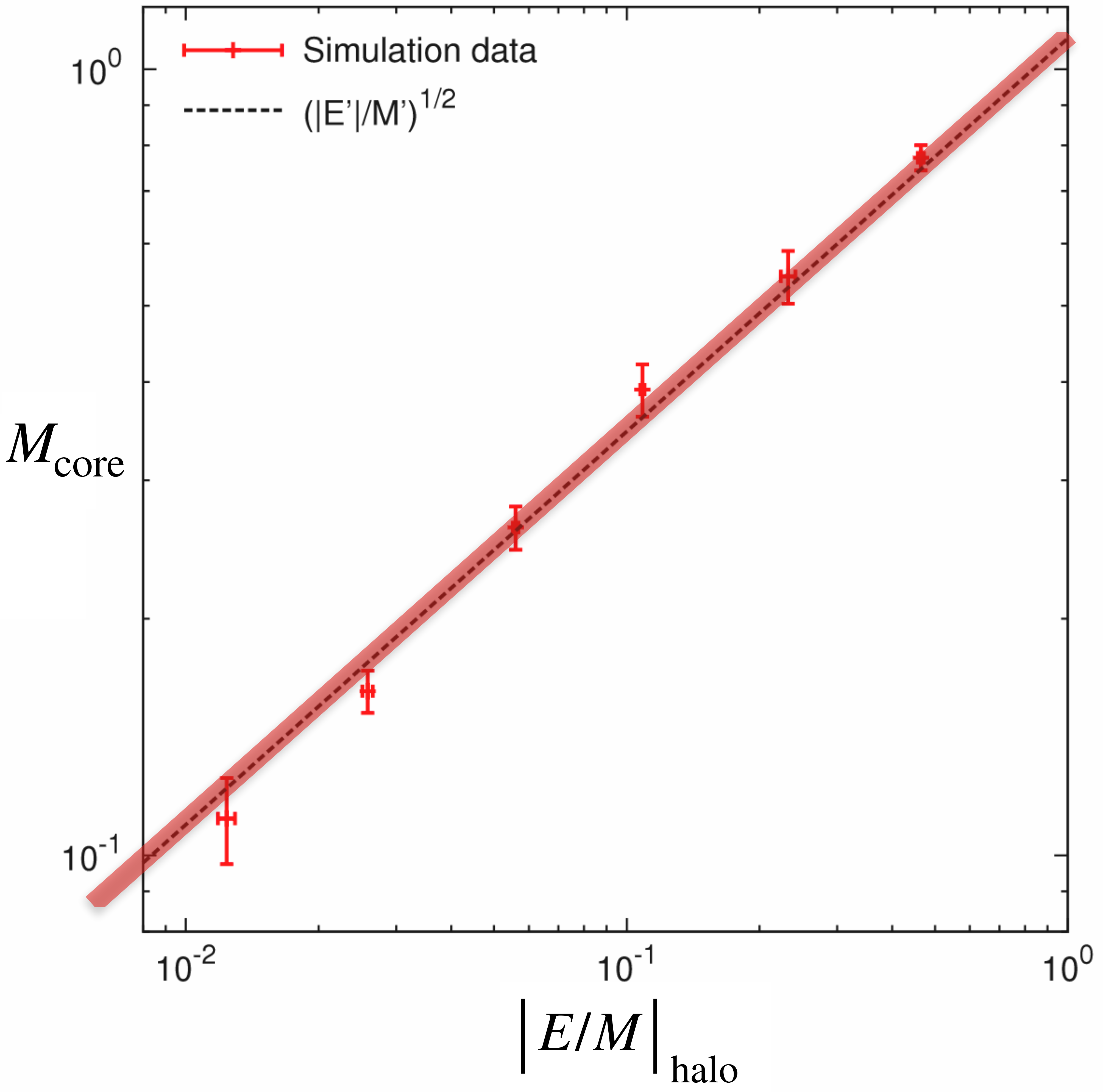
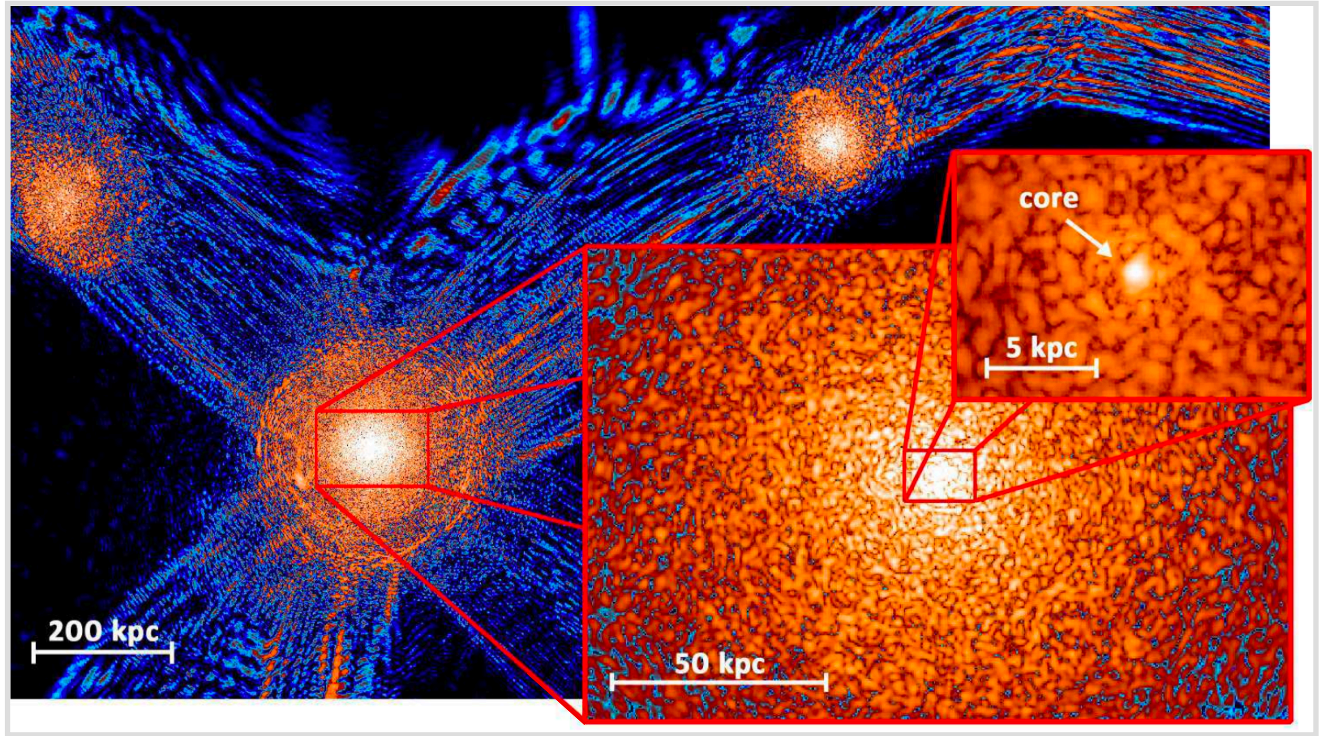


Schive et al
1406.6586, 1407.7762



Core — halo relation



Schive et al 1406.6586, 1407.7762

Bar, et al 1805.00122, 1903.03402

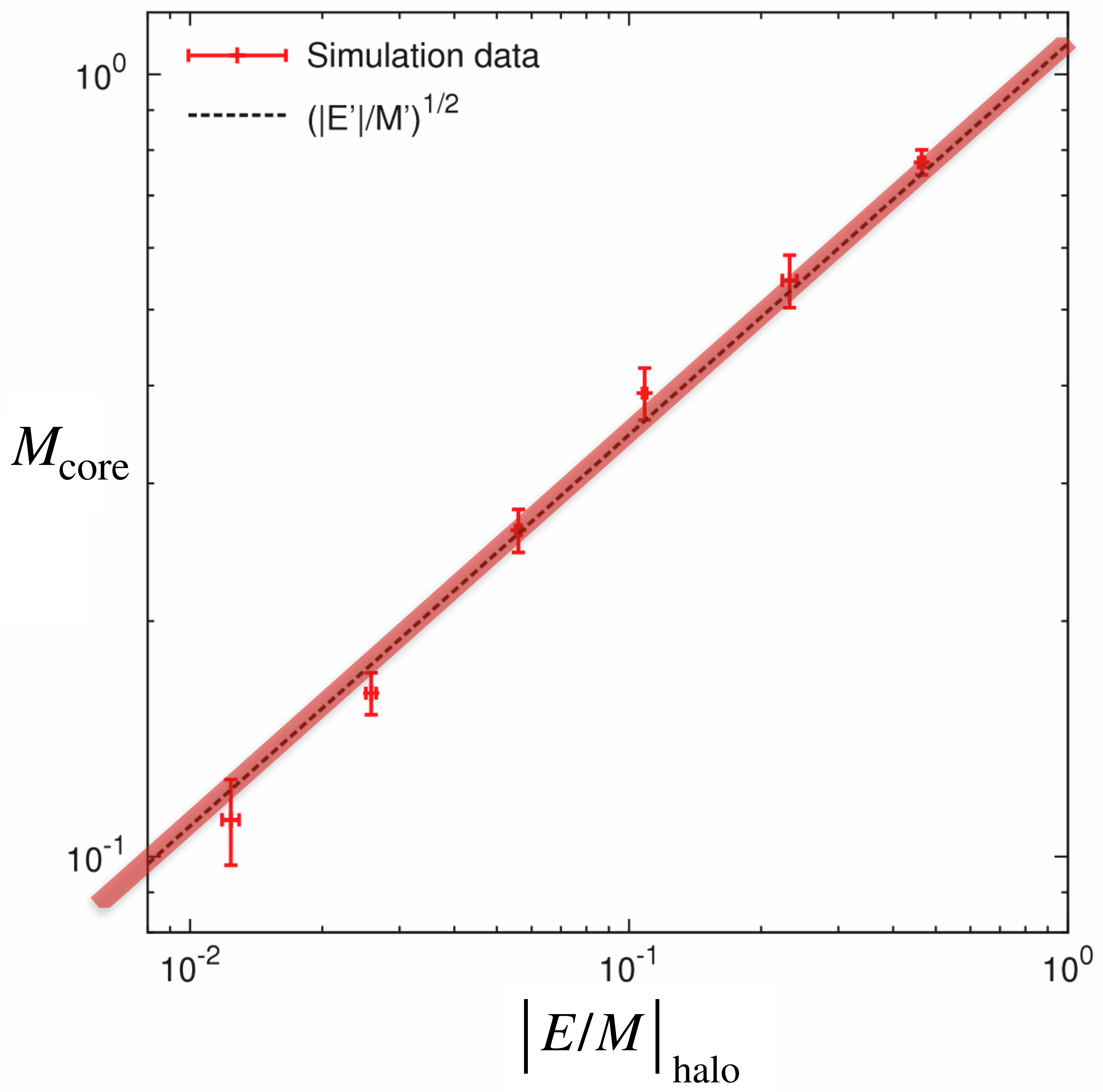
$$\boxed{\left.\frac{K}{M}\right|_{\rm core} = \left.\frac{K}{M}\right|_{\rm halo}}$$

K/M: kinetic energy/mass.

$$M = \int d^3x\,|\psi|^2$$

$$E = \int d^3x\left(\frac{|\nabla\psi|^2}{2m^2} + \frac{\Phi|\psi|^2}{2}\right)$$

$$K = \int d^3x\,\frac{|\nabla\psi|^2}{2m^2} = -E$$



Core — halo relation

Dynamical relaxation is fast enough for $m \lesssim 10^{-21}$ eV.

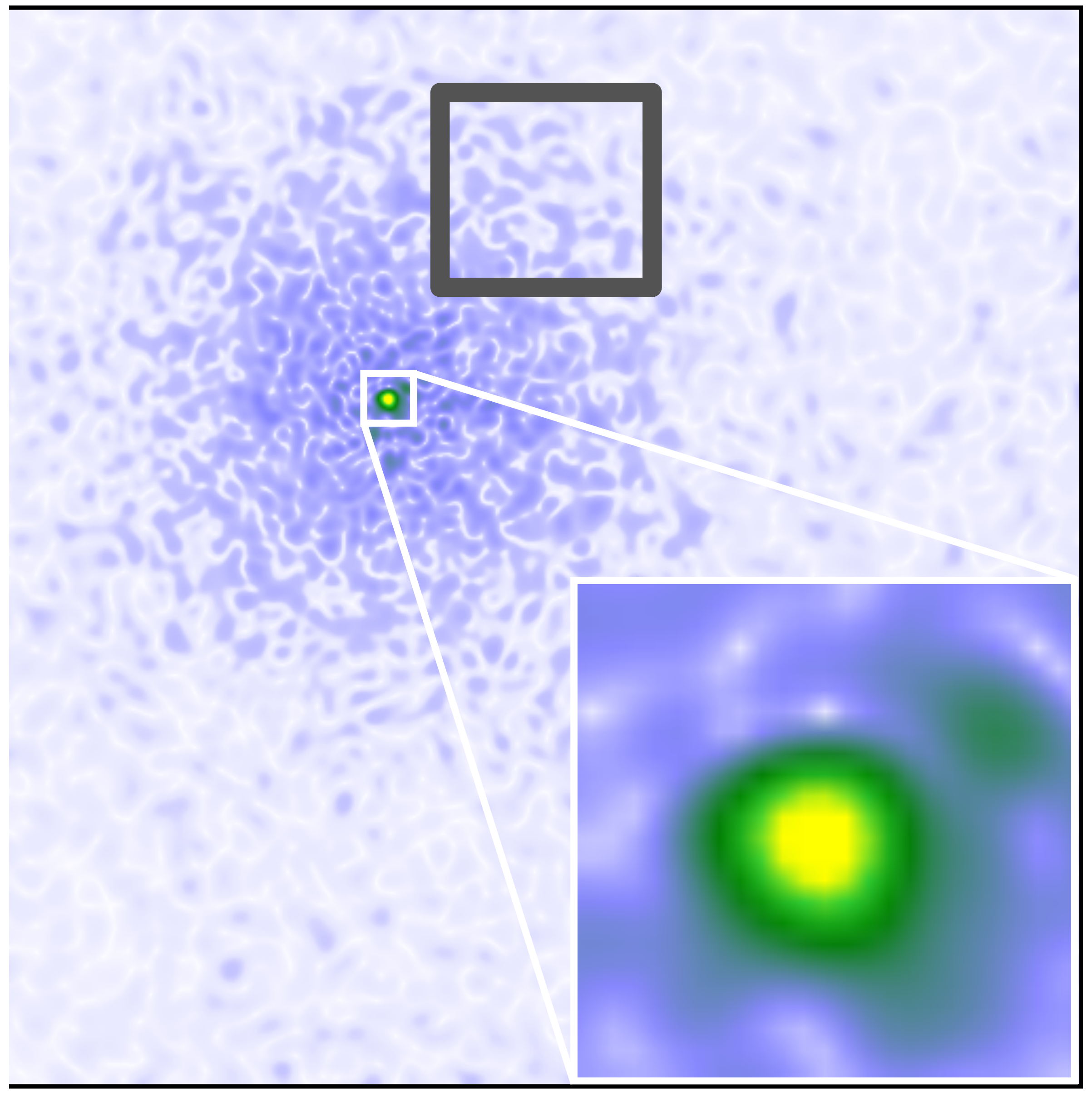
Bar, et al 1805.00122, 1903.03402

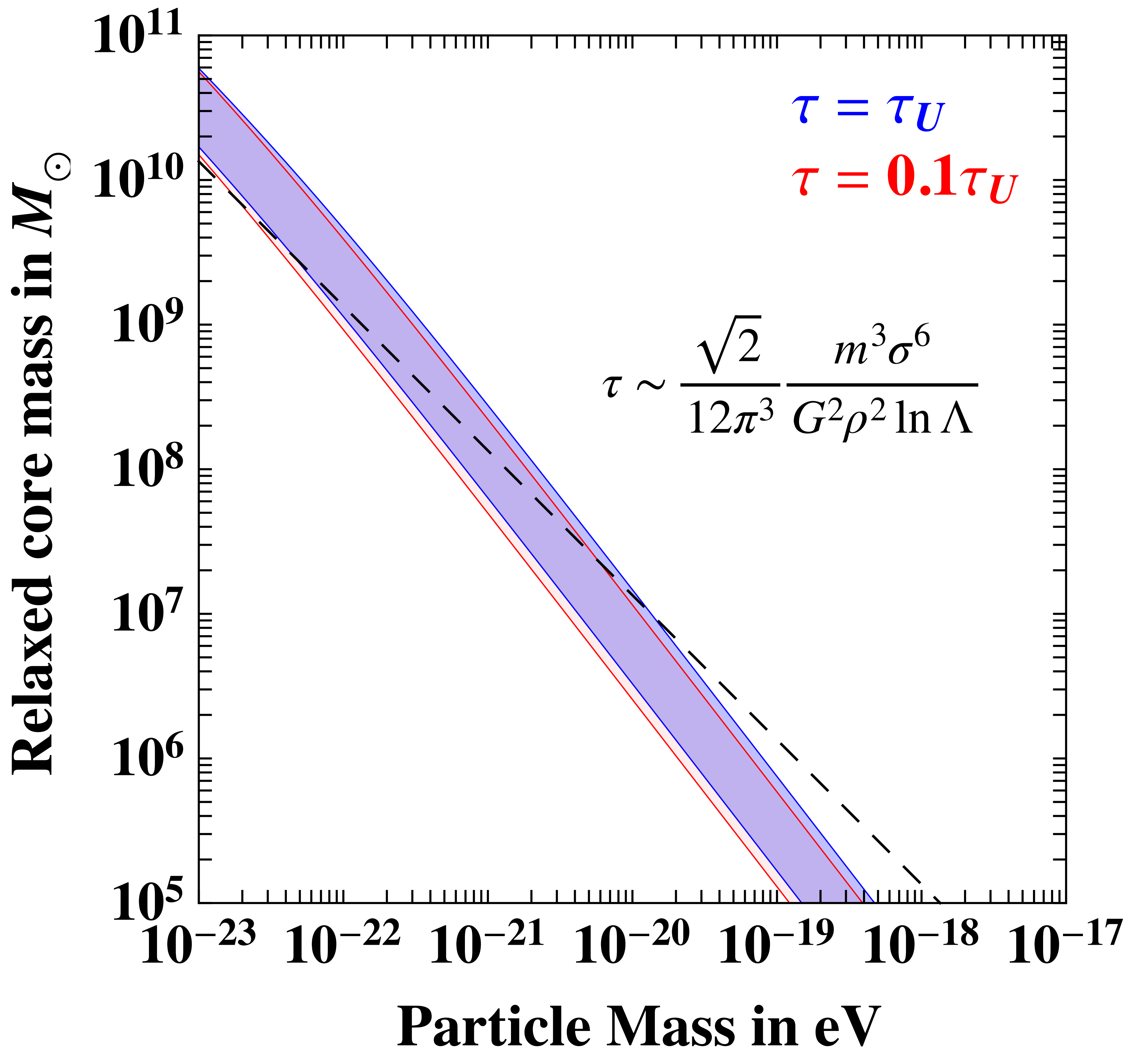
$$\boxed{\left.\frac{K}{M}\right|_{\text{core}} = \left.\frac{K}{M}\right|_{\text{halo}}}$$

K/M: kinetic energy/mass.

Levkov et al 2018

Hui et al 2017,
Bar-Or, Tremaine 2018,
Chen et al 2021

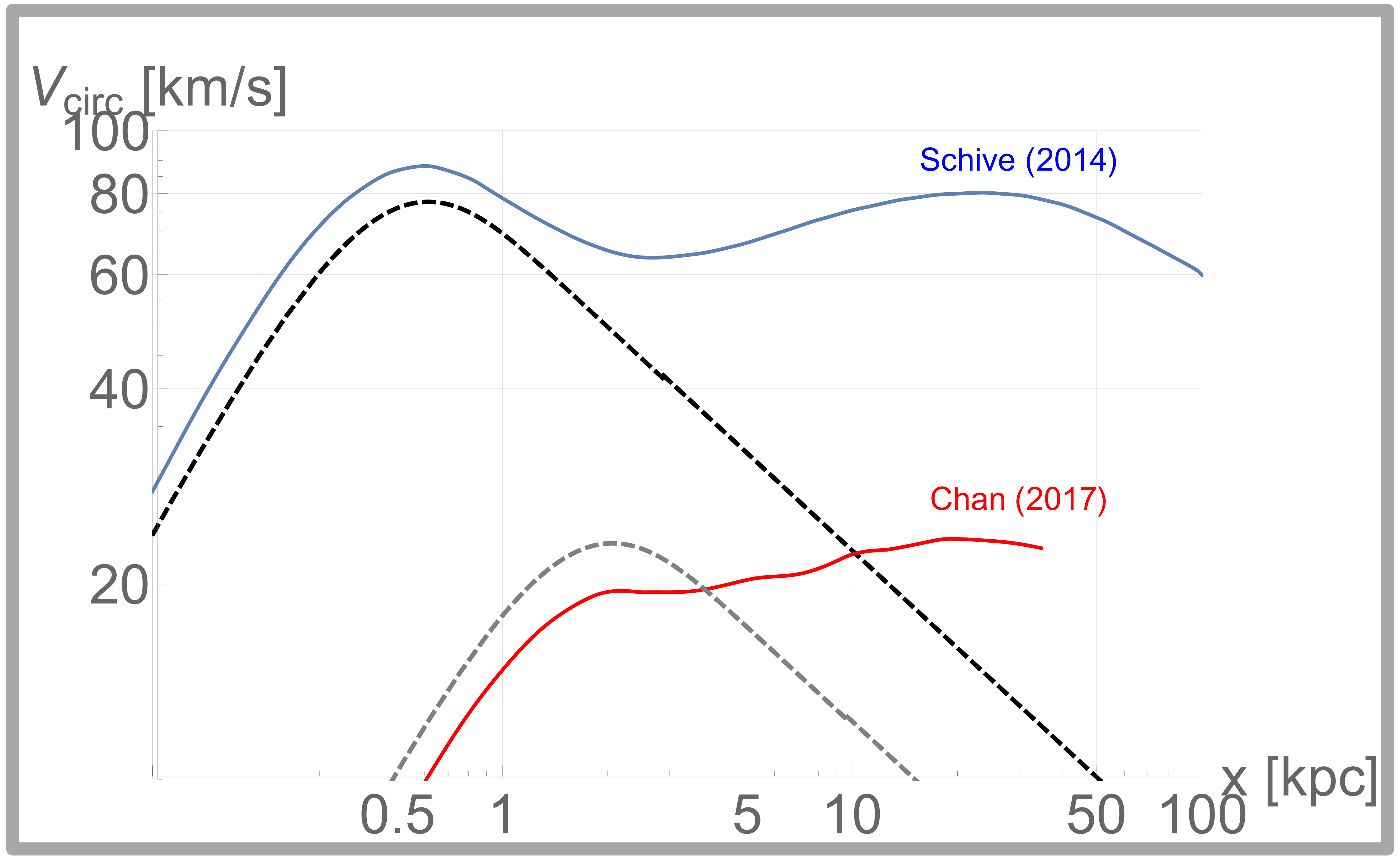




Core — halo relation

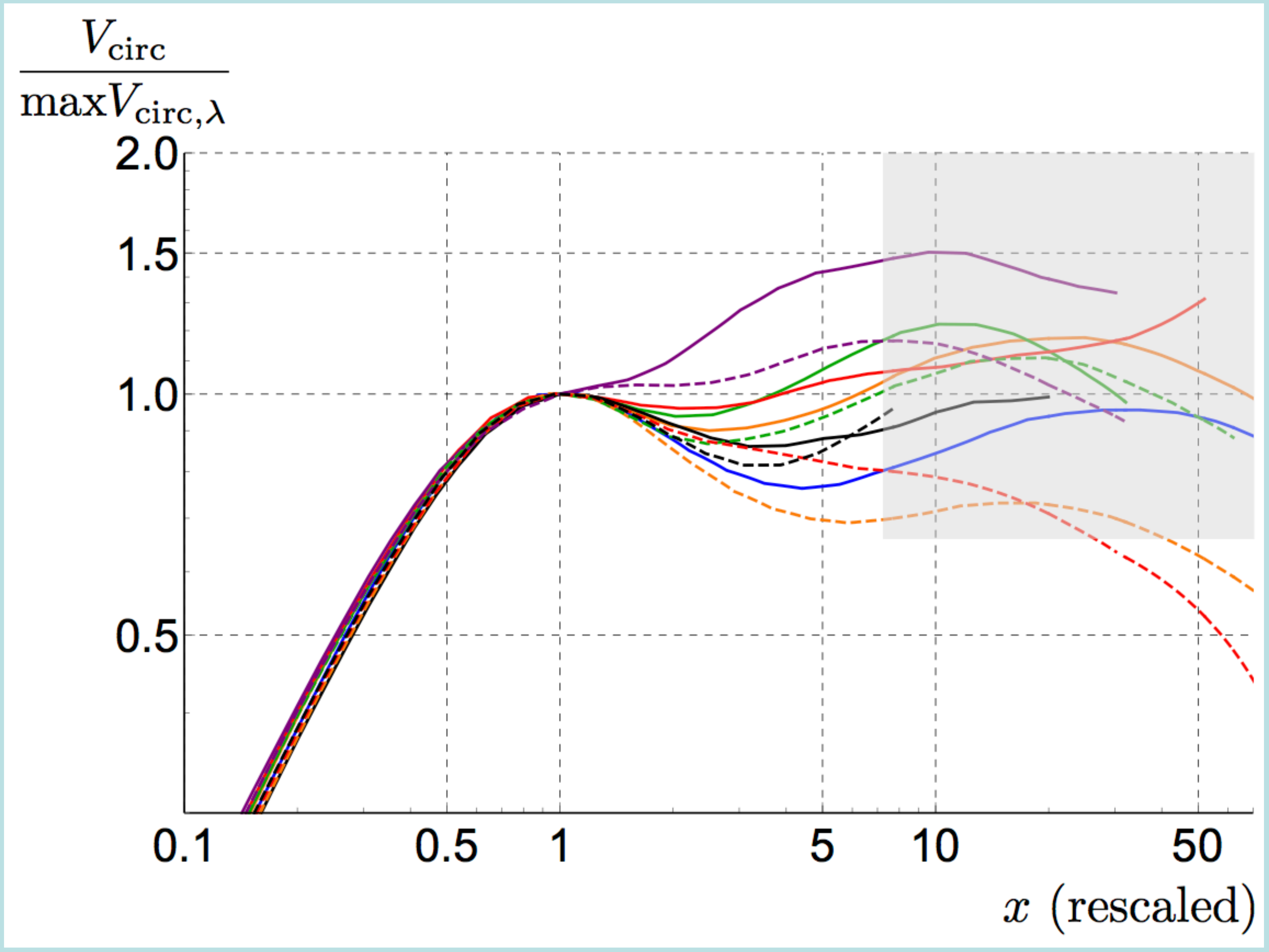
$$\left.\frac{K}{M}\right|_{\text{core}} = \left.\frac{K}{M}\right|_{\text{halo}}$$

Rotation curves from simulations:

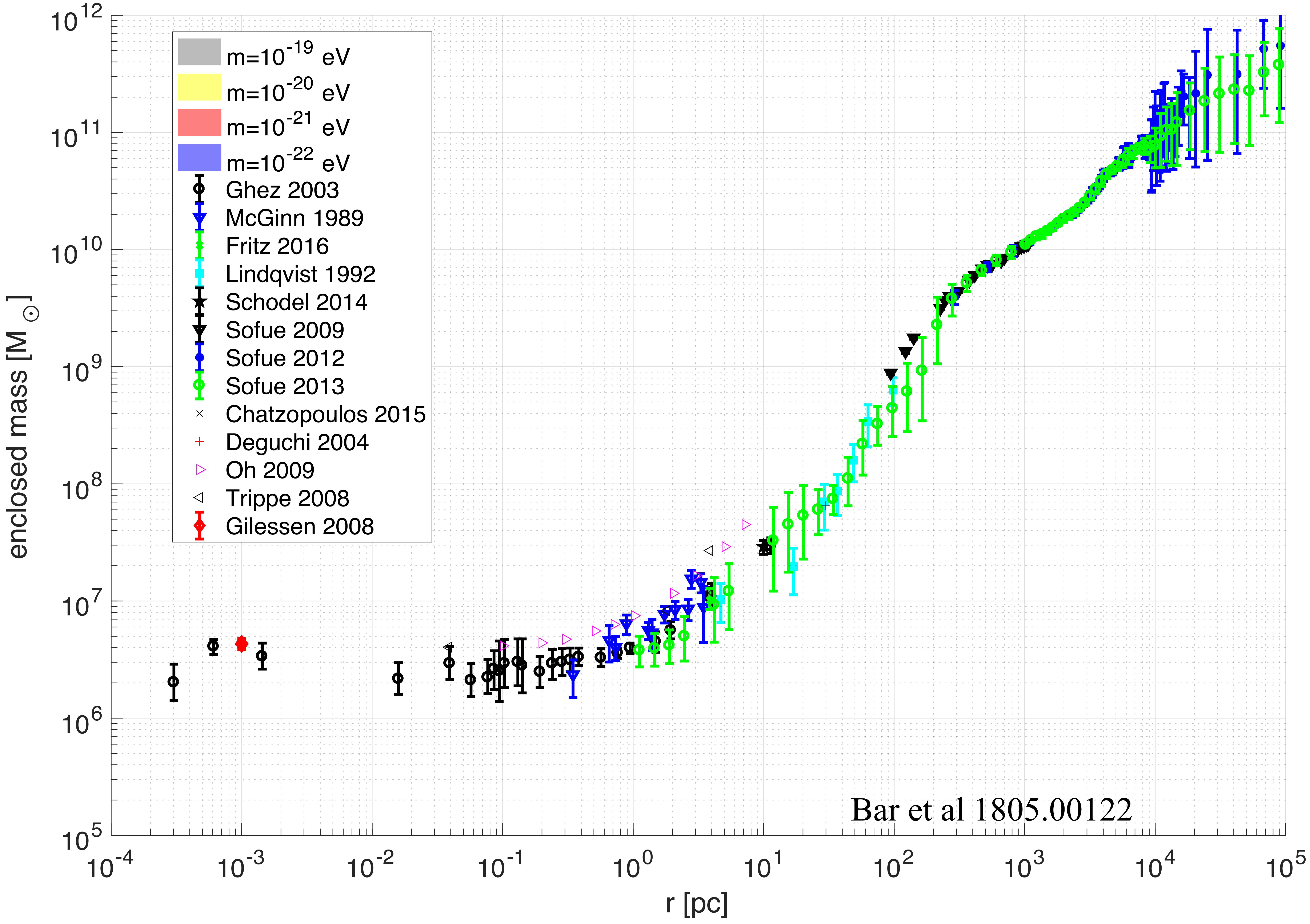


Core — halo relation

$$\boxed{\left.\frac{K}{M}\right|_{\text{core}} = \left.\frac{K}{M}\right|_{\text{halo}}}$$

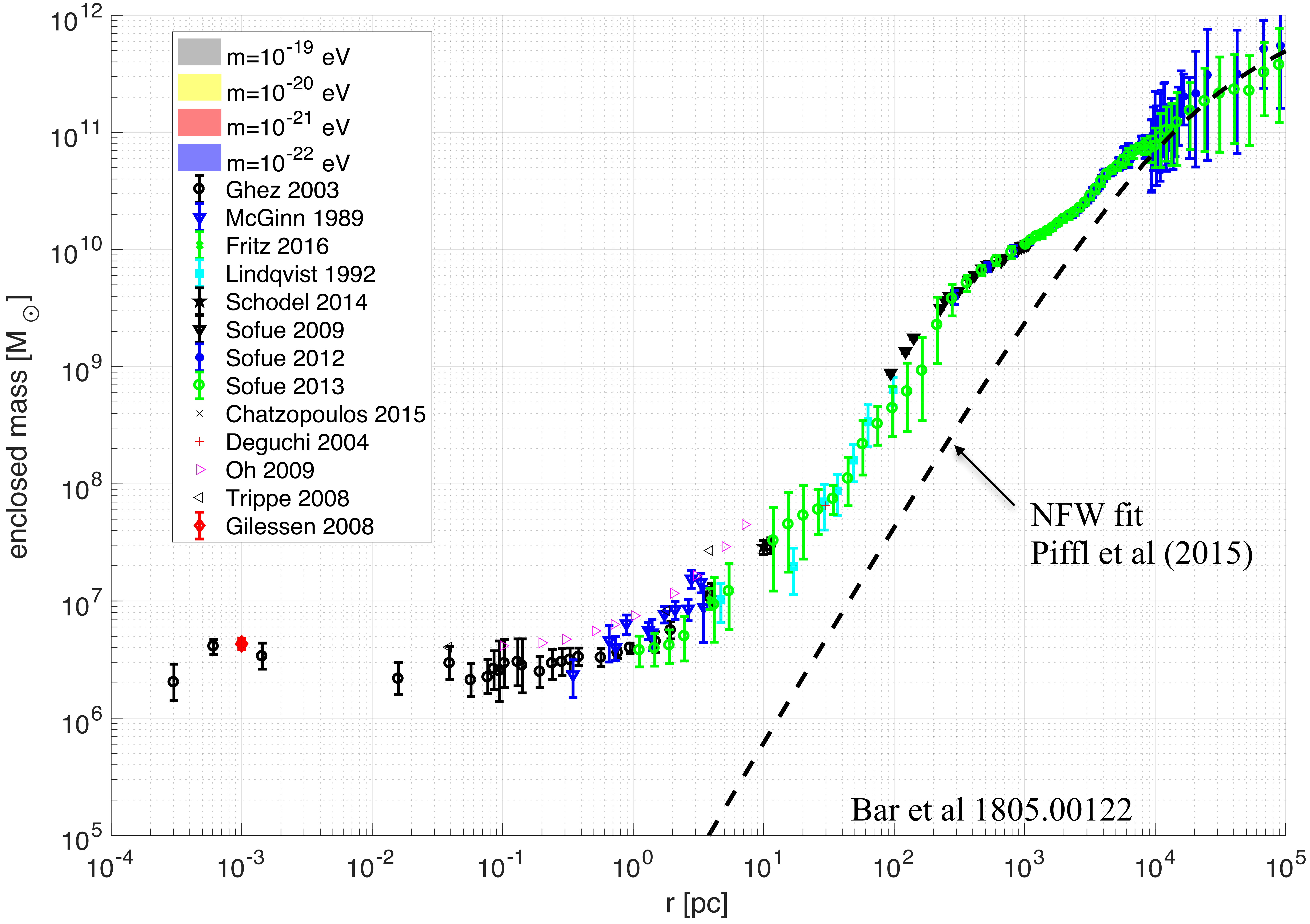


(Estimated) radially-averaged mass profile of the Milky Way



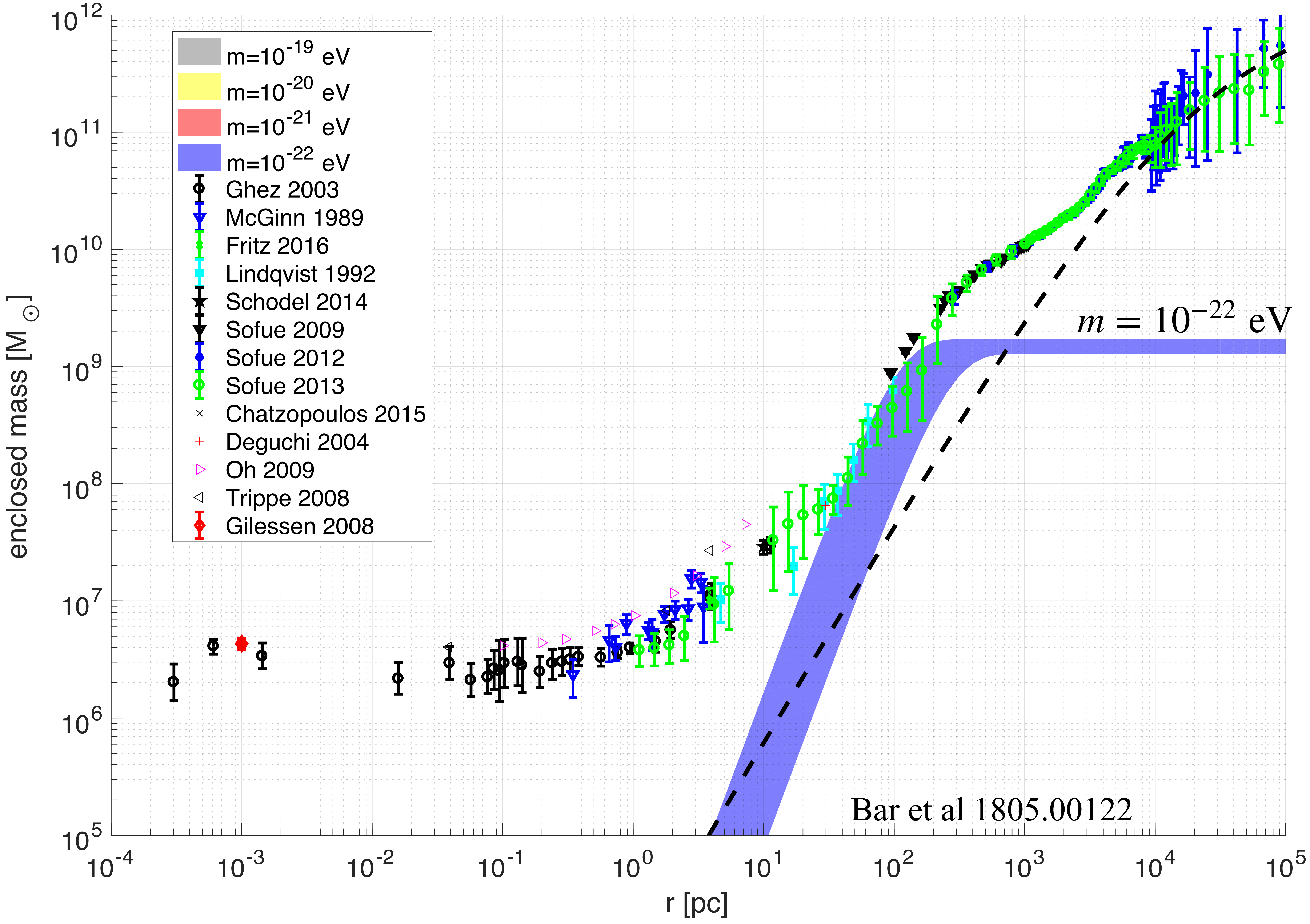
Massive cold dark matter:

thought to affect outer part of rotation curve



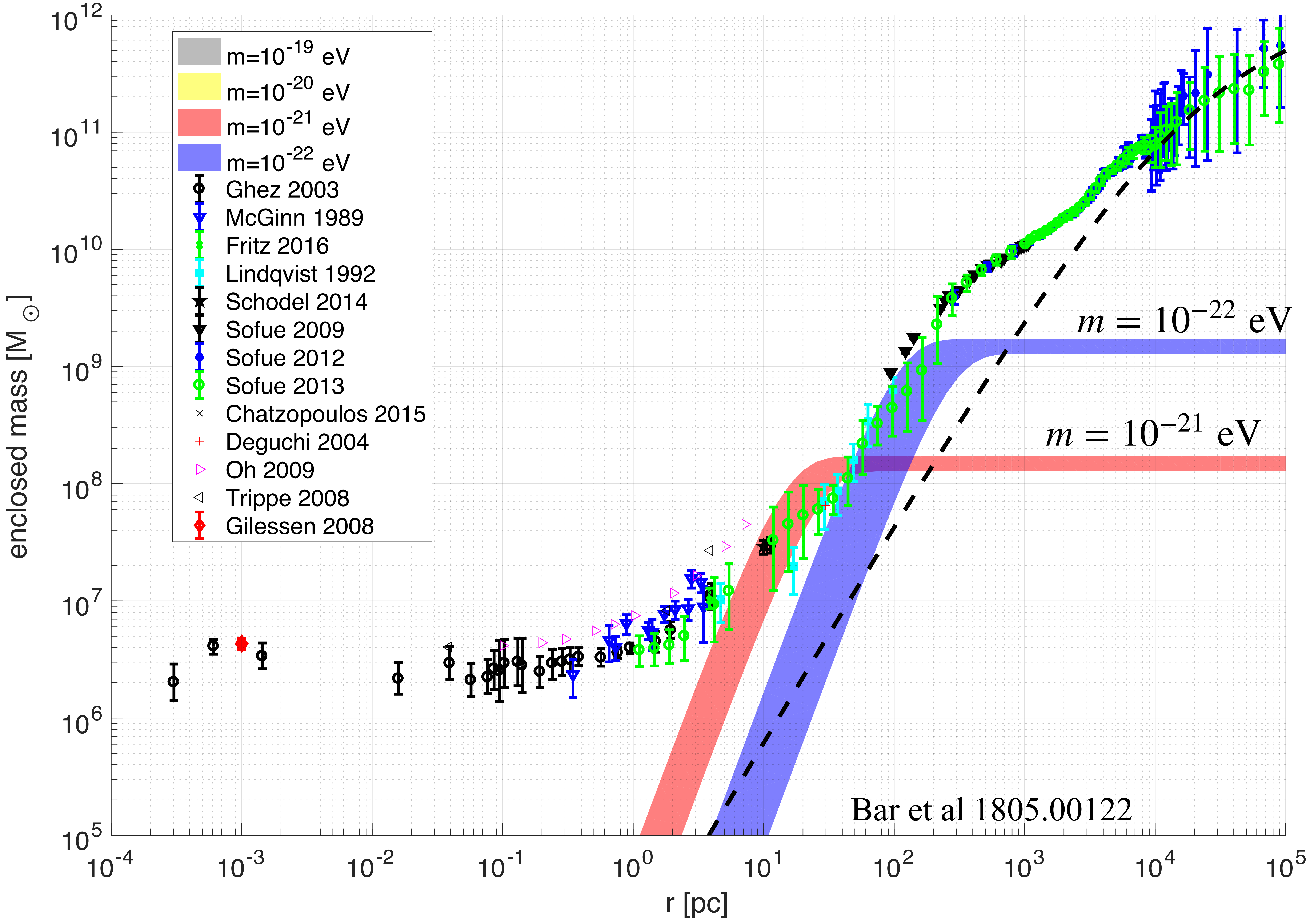
ULDM:

Affects the inner part of rotation curve



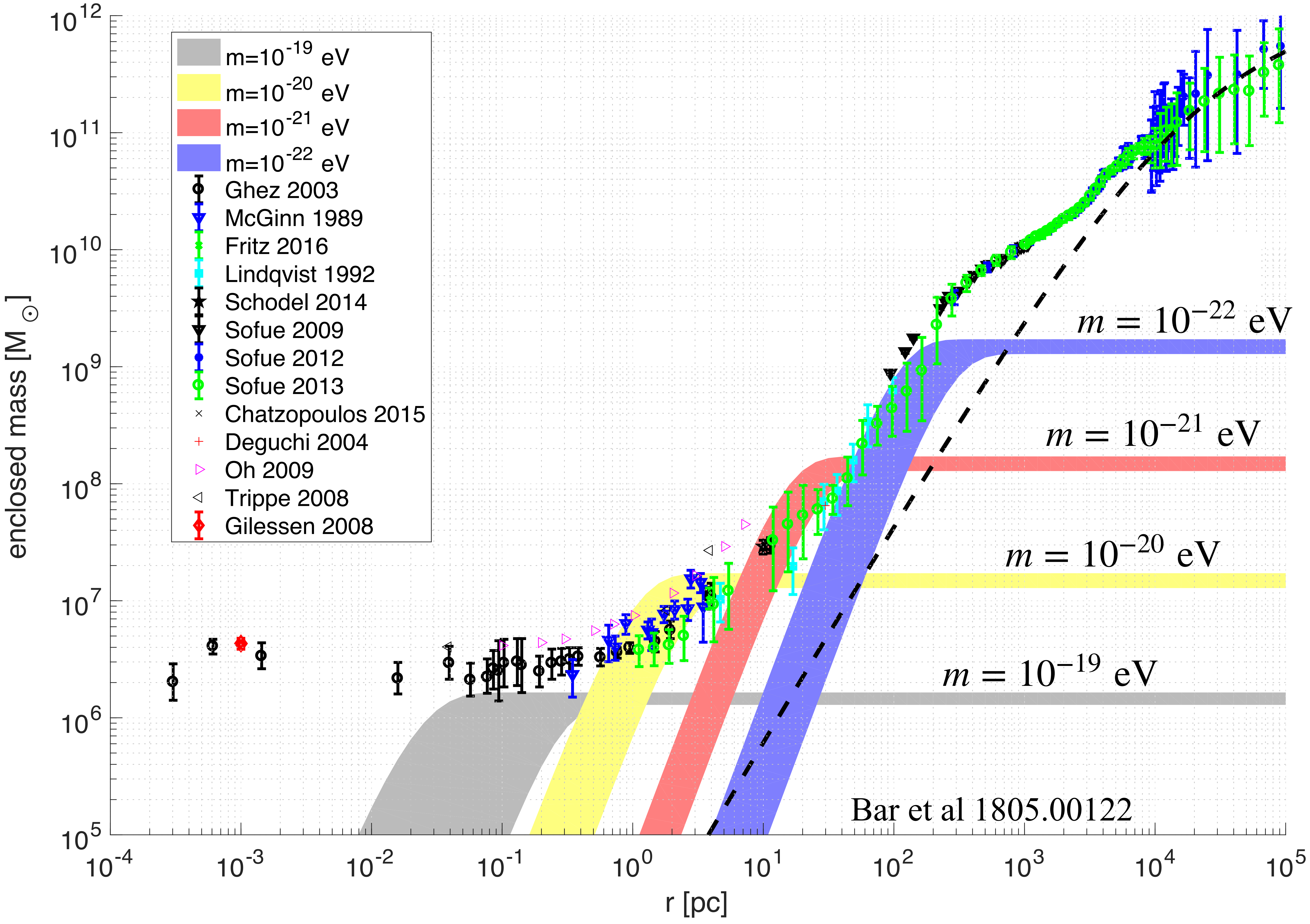
ULDM:

Affects the inner part of rotation curve



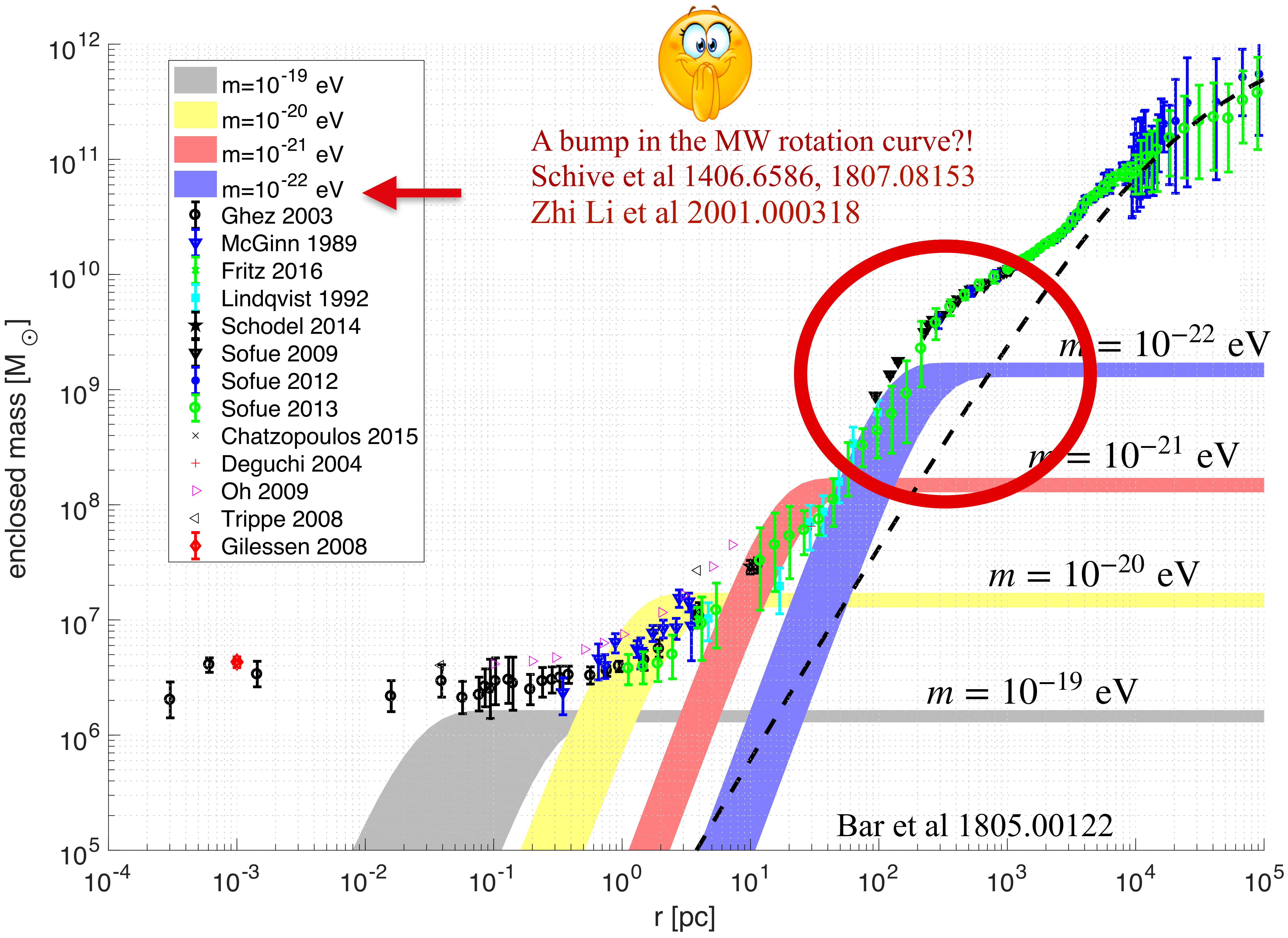
ULDM:

Affects the inner part of rotation curve



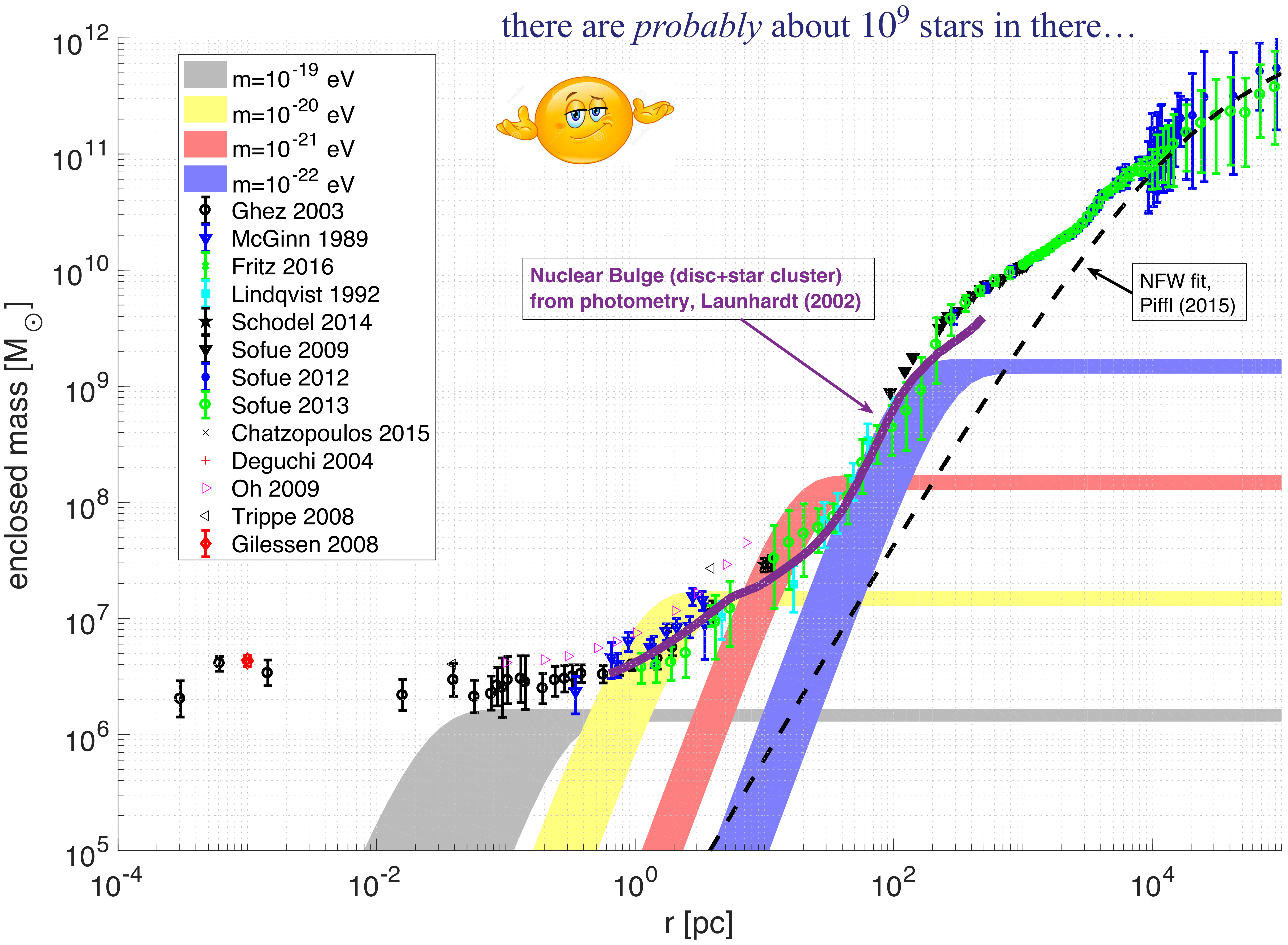
ULDM:

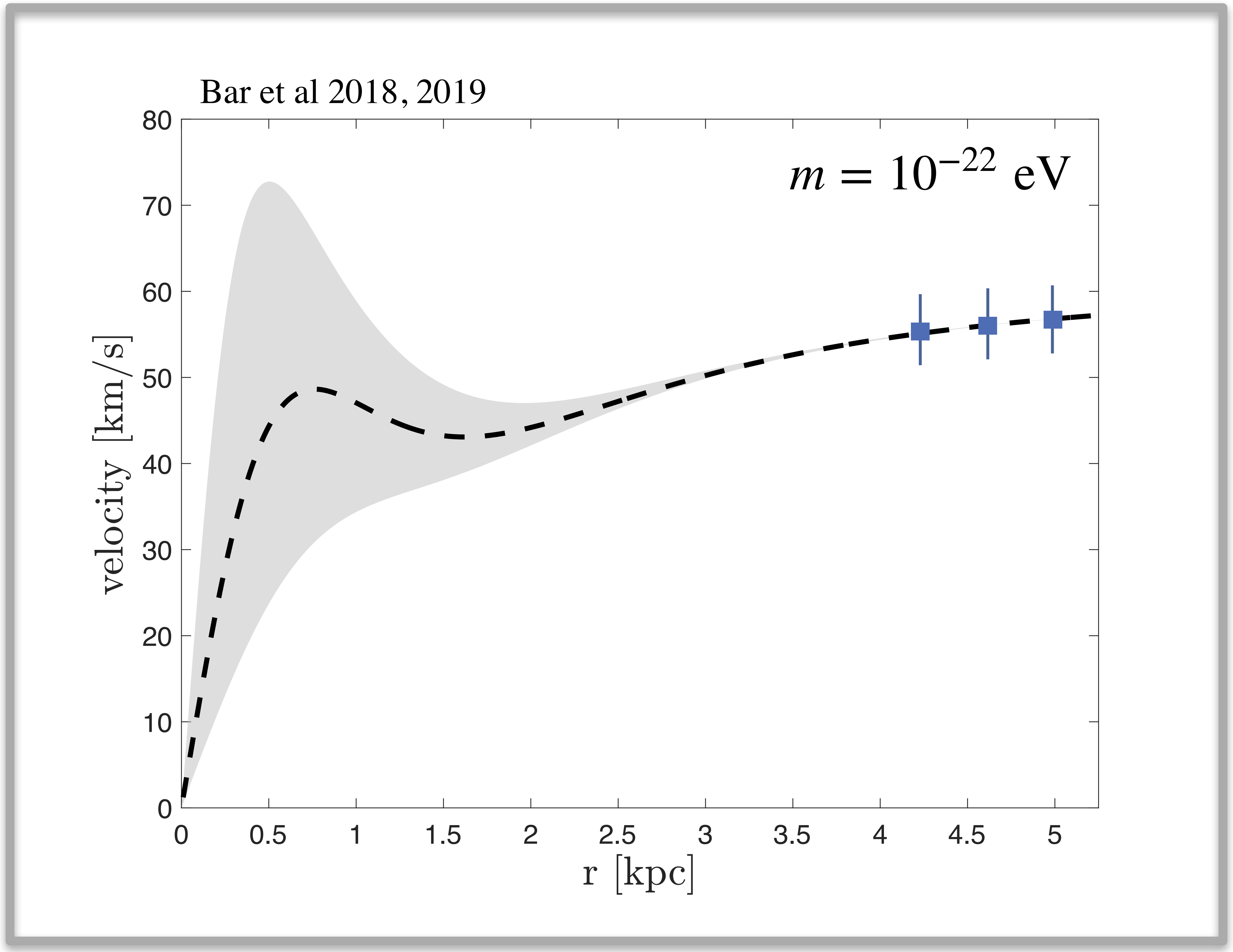
Affects the inner part of rotation curve



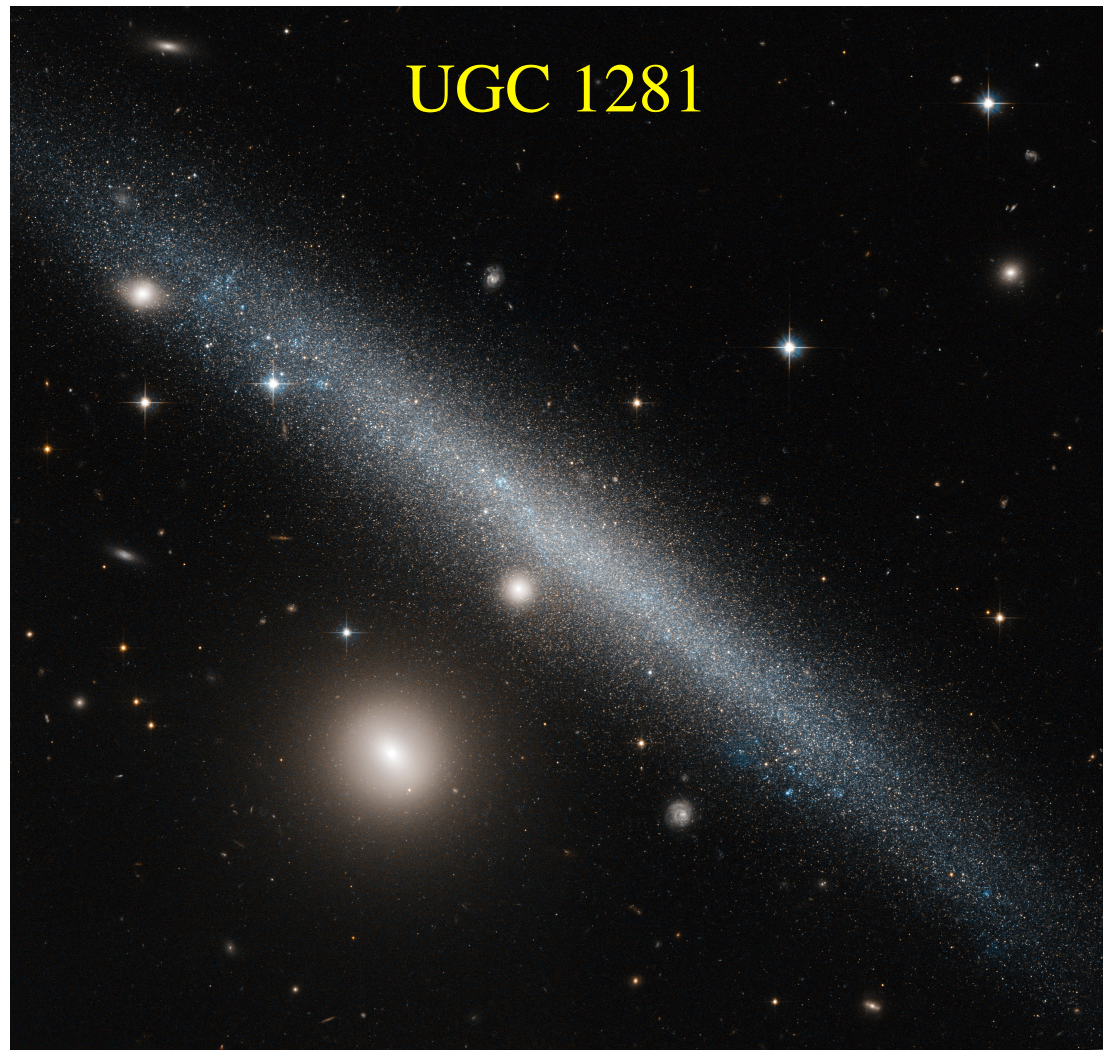
ULDM:

Affects the inner part of rotation curve

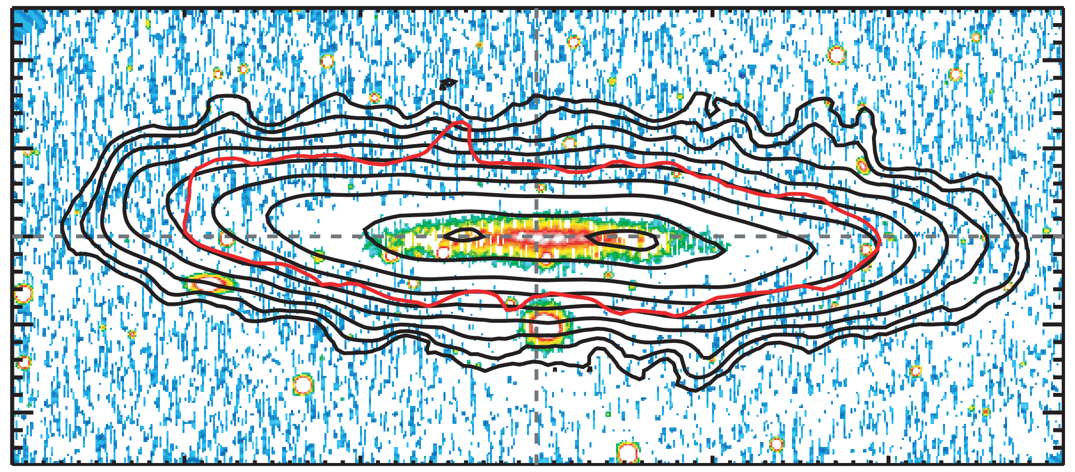


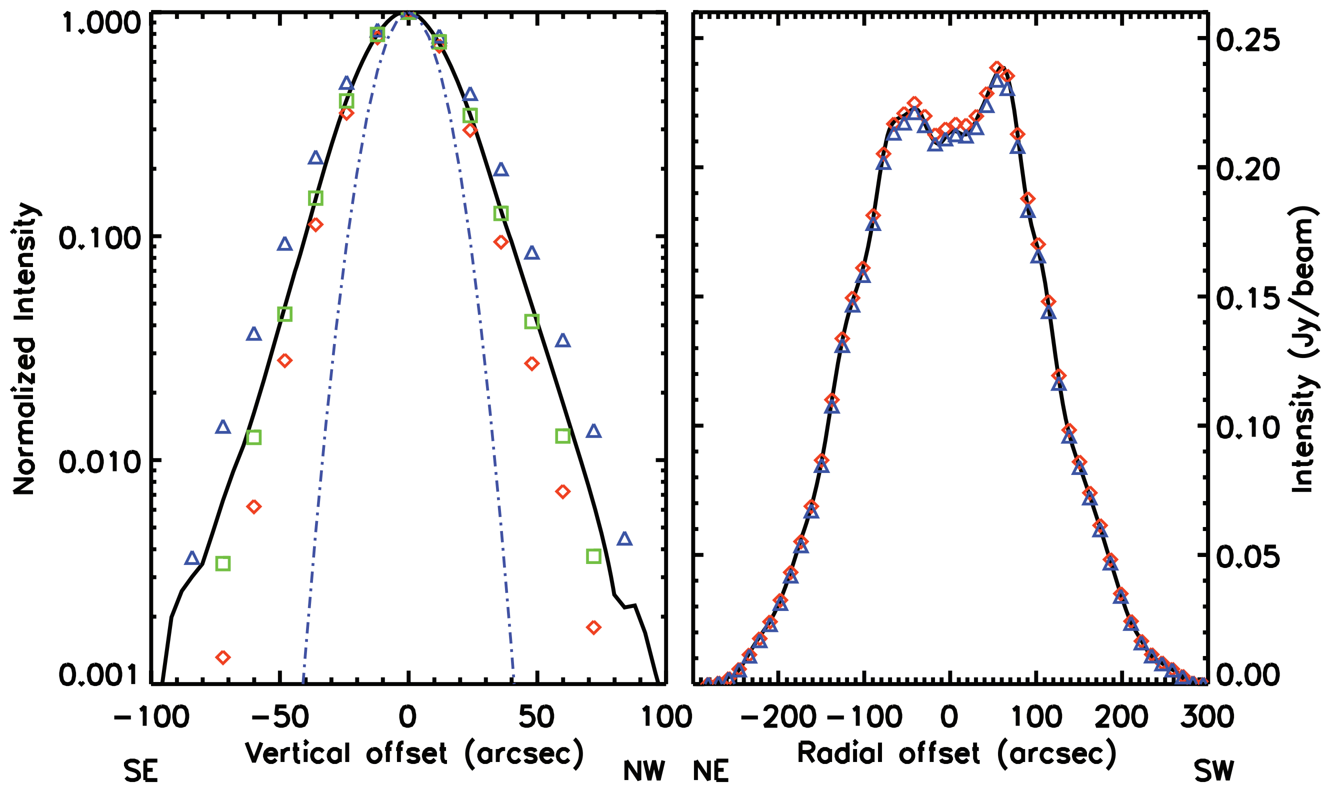


Bar et al 2018, 2019
$m = 10^{-22}$ eV
velocity [km/s]
r [kpc]
0
10
20
30
40
50
60
70
80
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

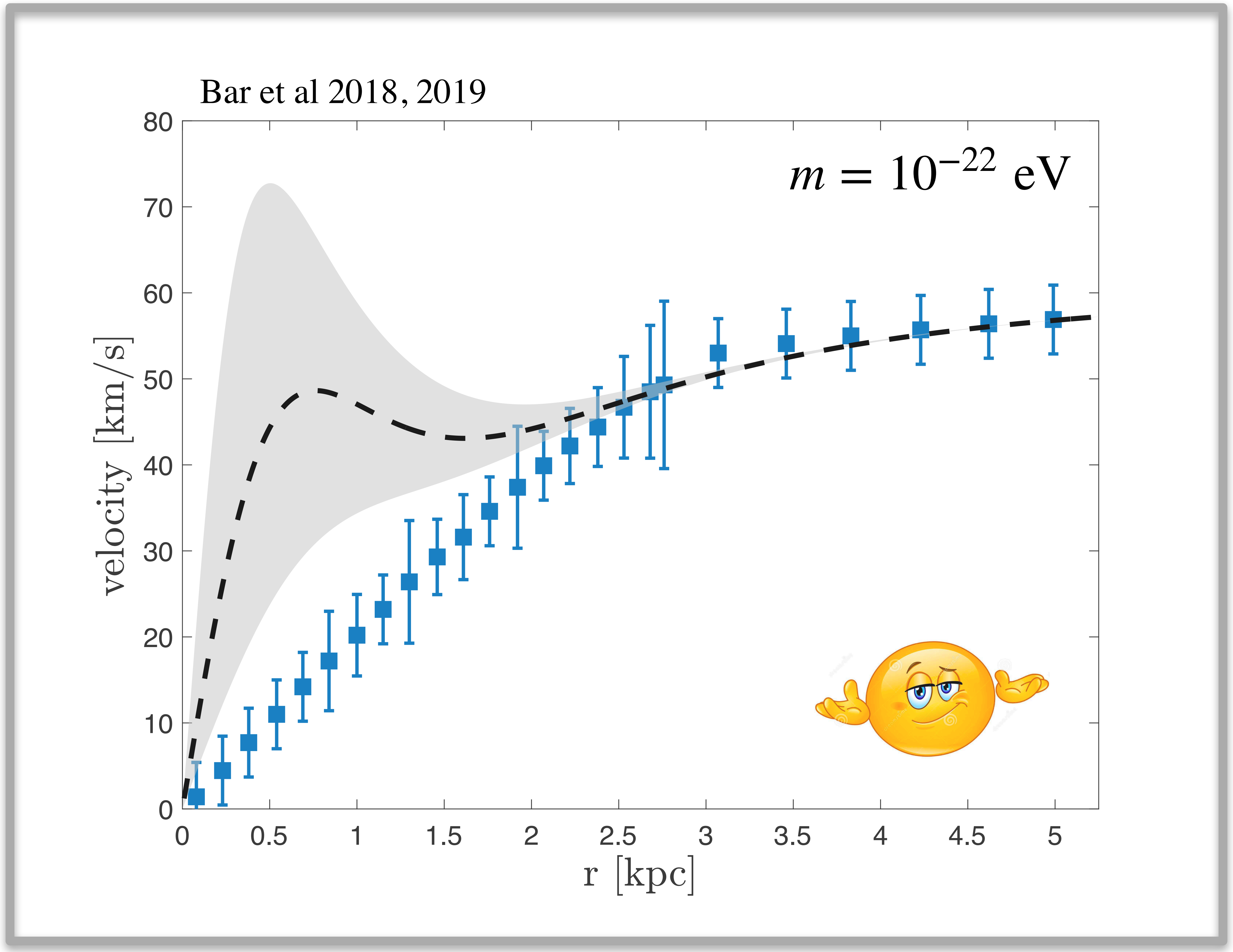


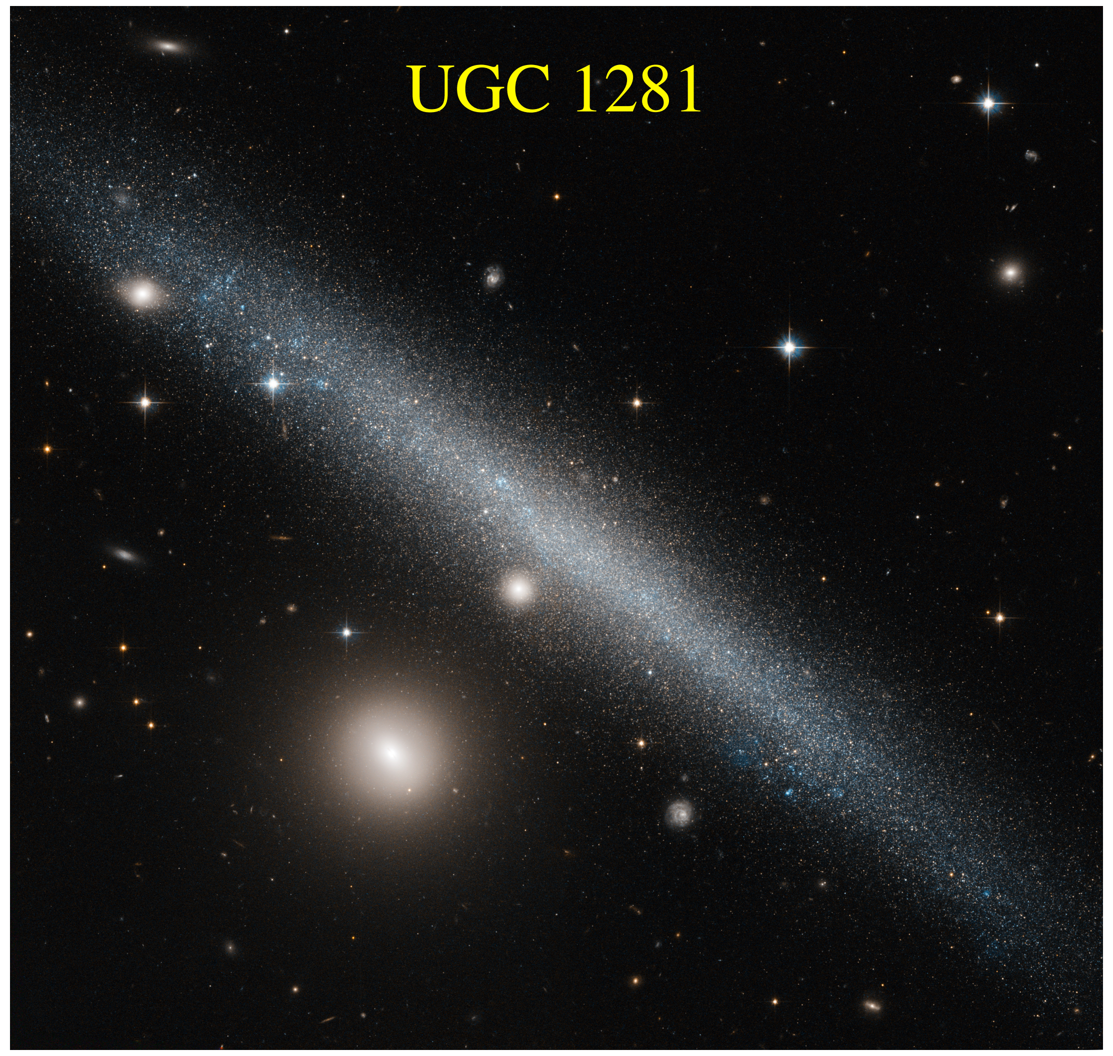
UGC 1281

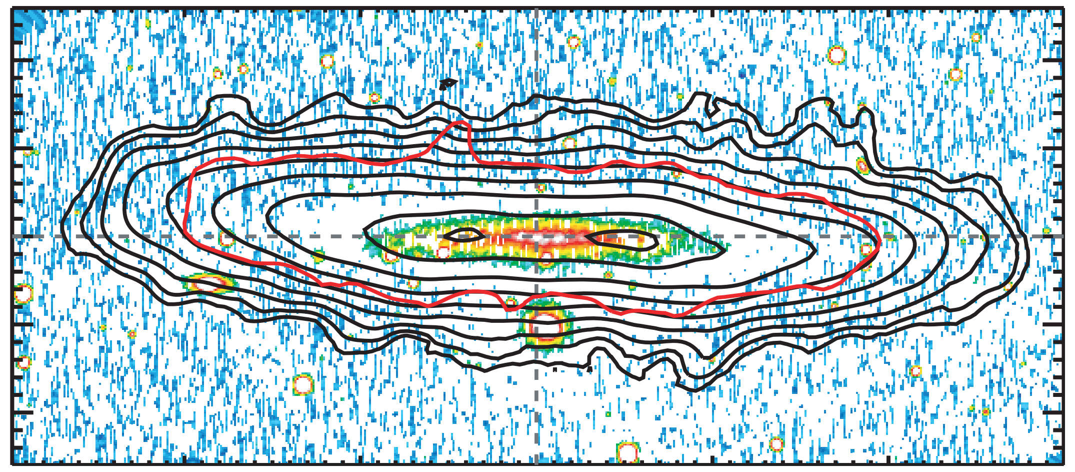


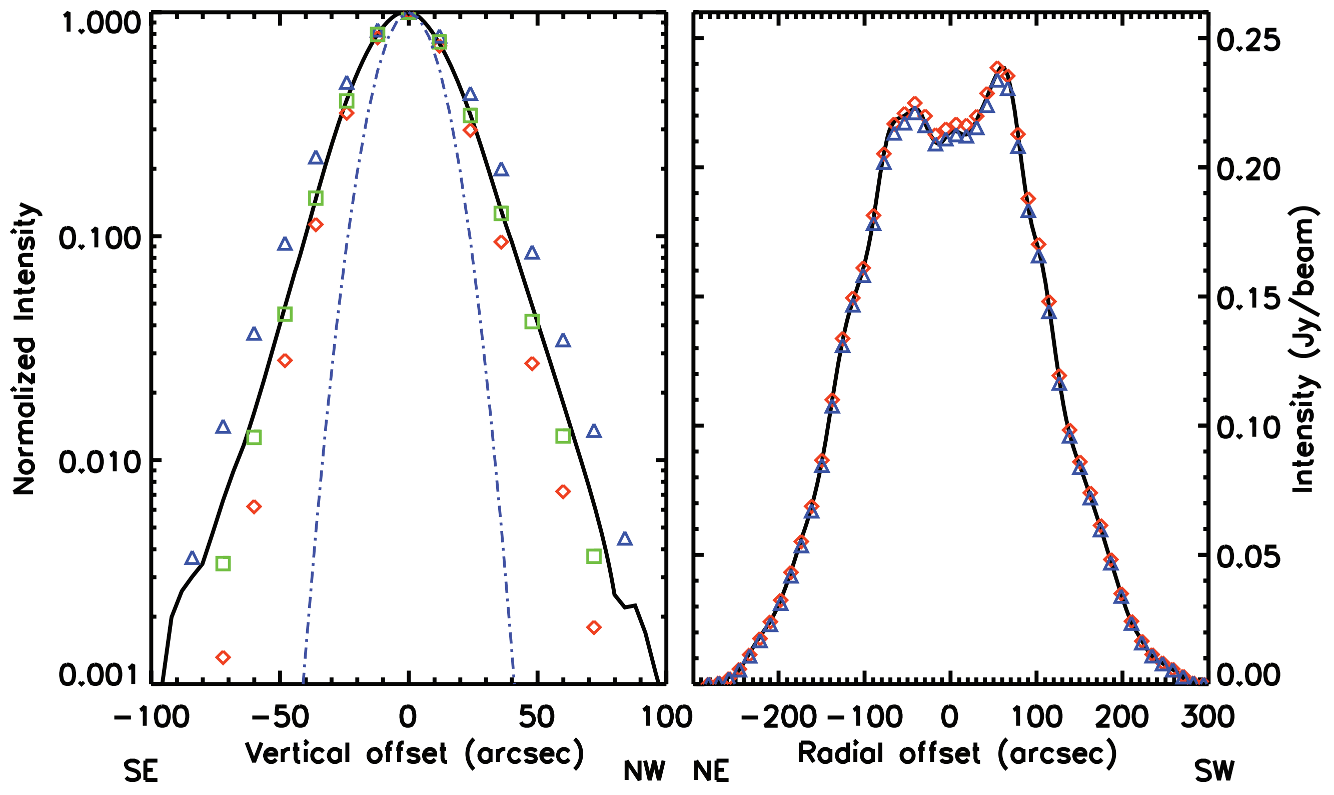


Normalized Intensity
1.000
0.100
0.010
0.001
−100
−50
0
50
100
SE
Vertical offset (arcsec)
NW
NE
−200
−100
0
100
200
300
Radial offset (arcsec)
SW
0.25
0.20
0.15
0.10
0.05
0.00
Intensity (Jy/beam)







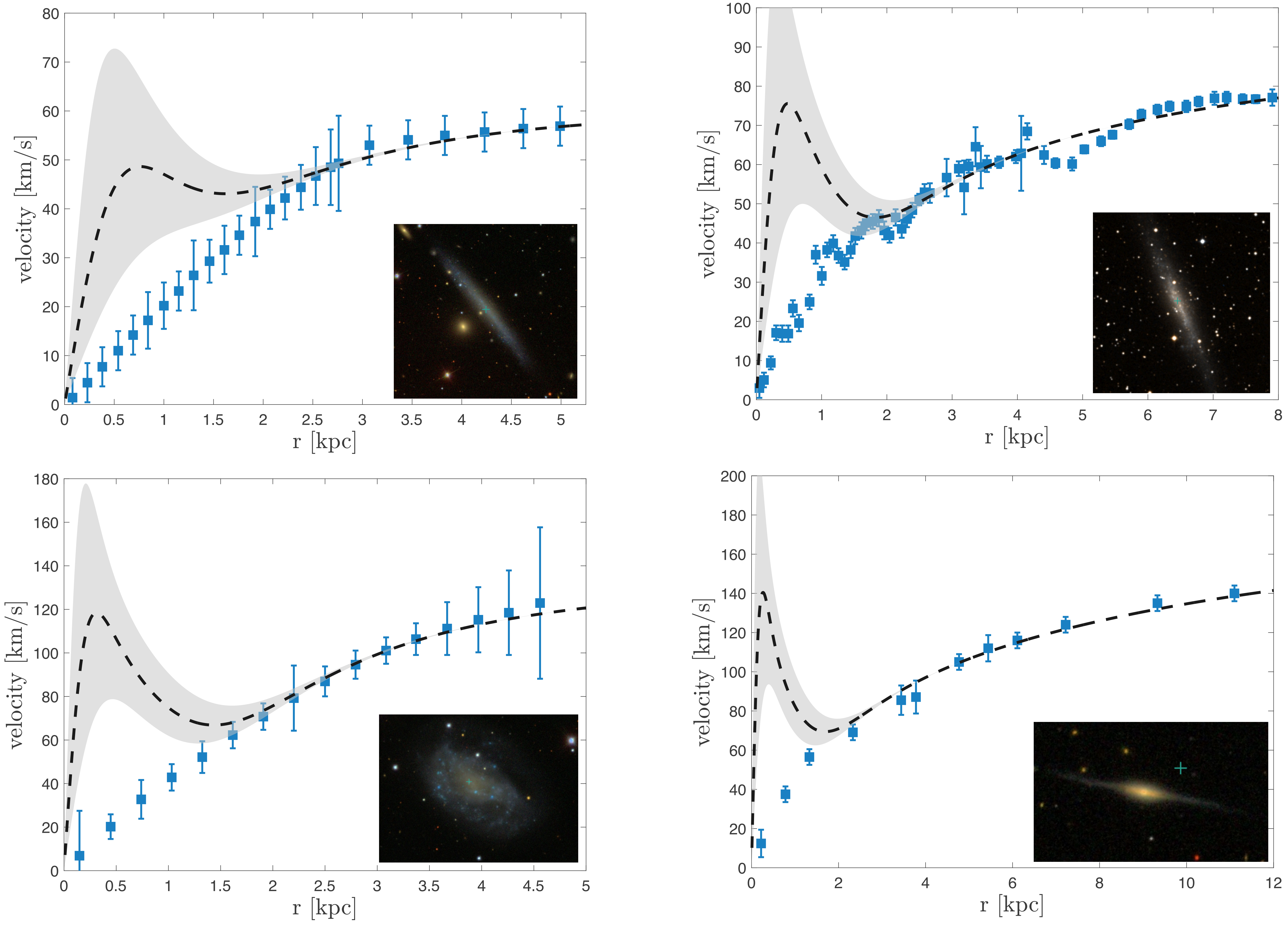


- Where is the core?
- This *could* have been spectacular…

A lower limit on the mass of dark matter, with **gravity alone**

m_X

10^{-21} eV



A lower limit on the mass of dark matter, with **gravity alone**

m_X

10^{-21} eV

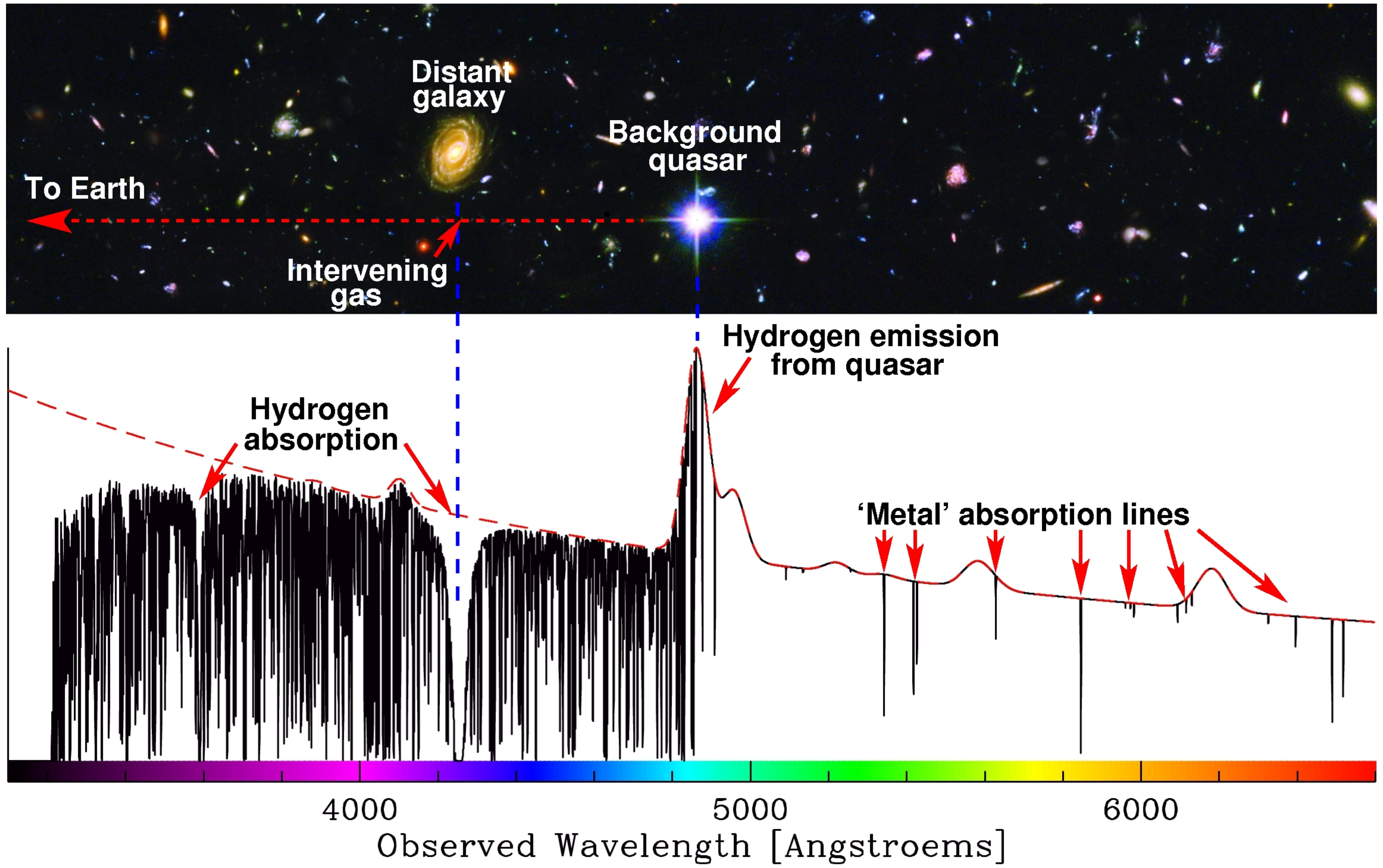
There are complimentary observables

m_X

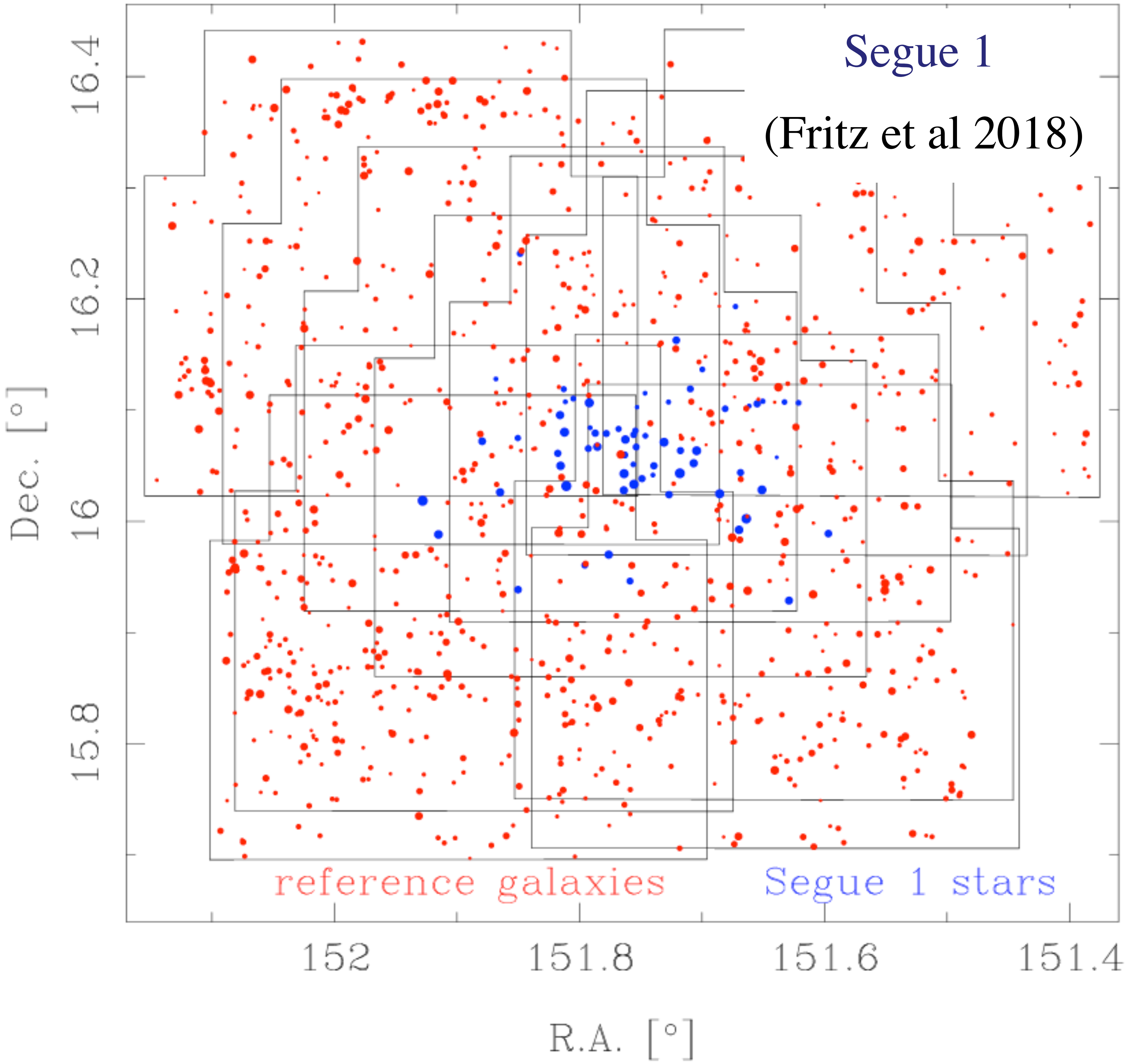
10^{-21} eV $\rightarrow$ 10^{-18} eV ?

There are complimentary observables

Kobayashi et al 2017; Armengaud et al 2017; …



Bar-Or, Fouvry, Tremaine 2018, 2020;
Dalal, Kravstov 2022, …



m_X

10^{-21} eV $\rightarrow$ 10^{-18} eV ?

There are complimentary observables

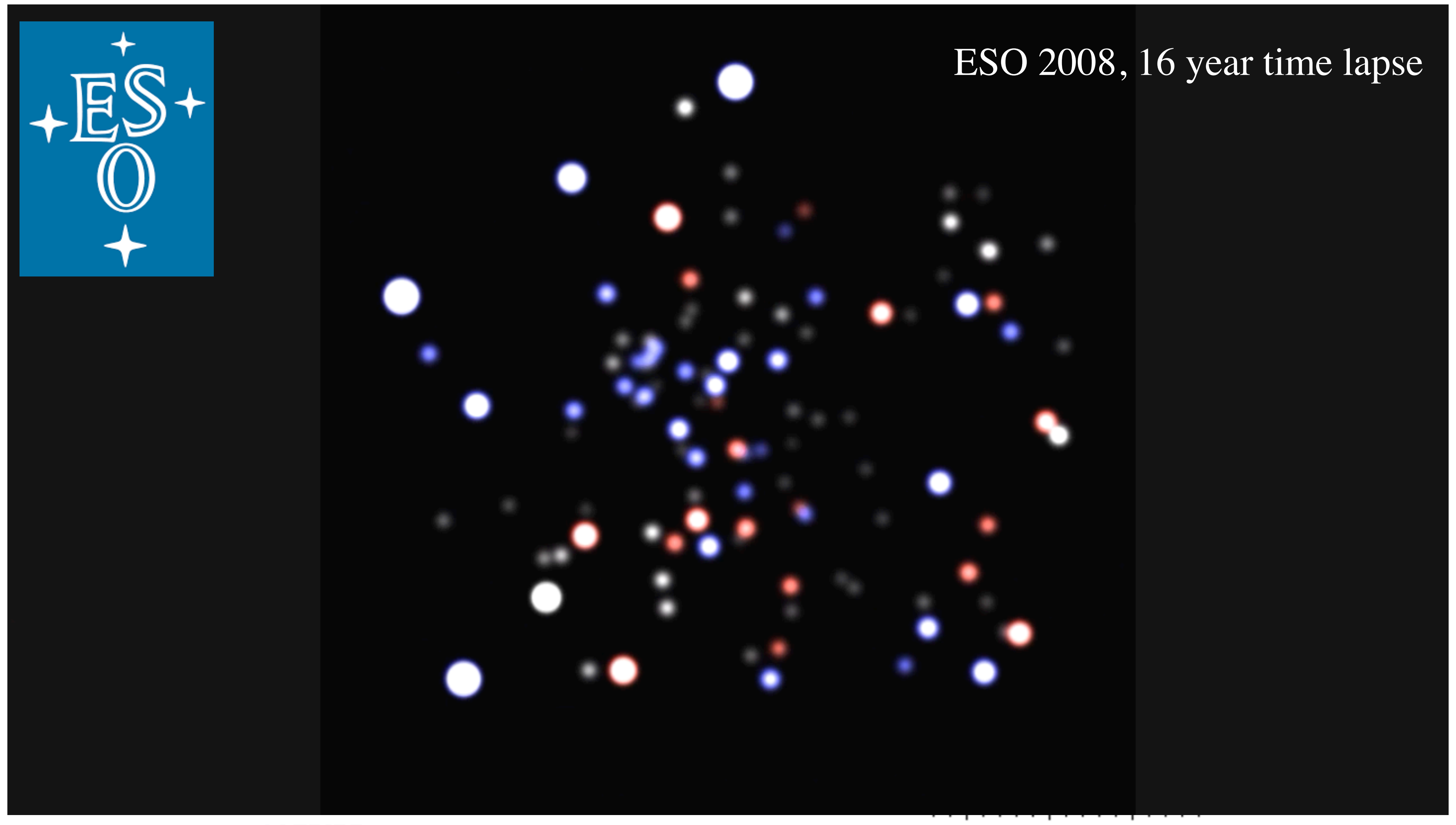
Khmelnitsky & Rubakov 1309.5888,
Poryako et al 1810.03227 (Parkes pulsar timing array)

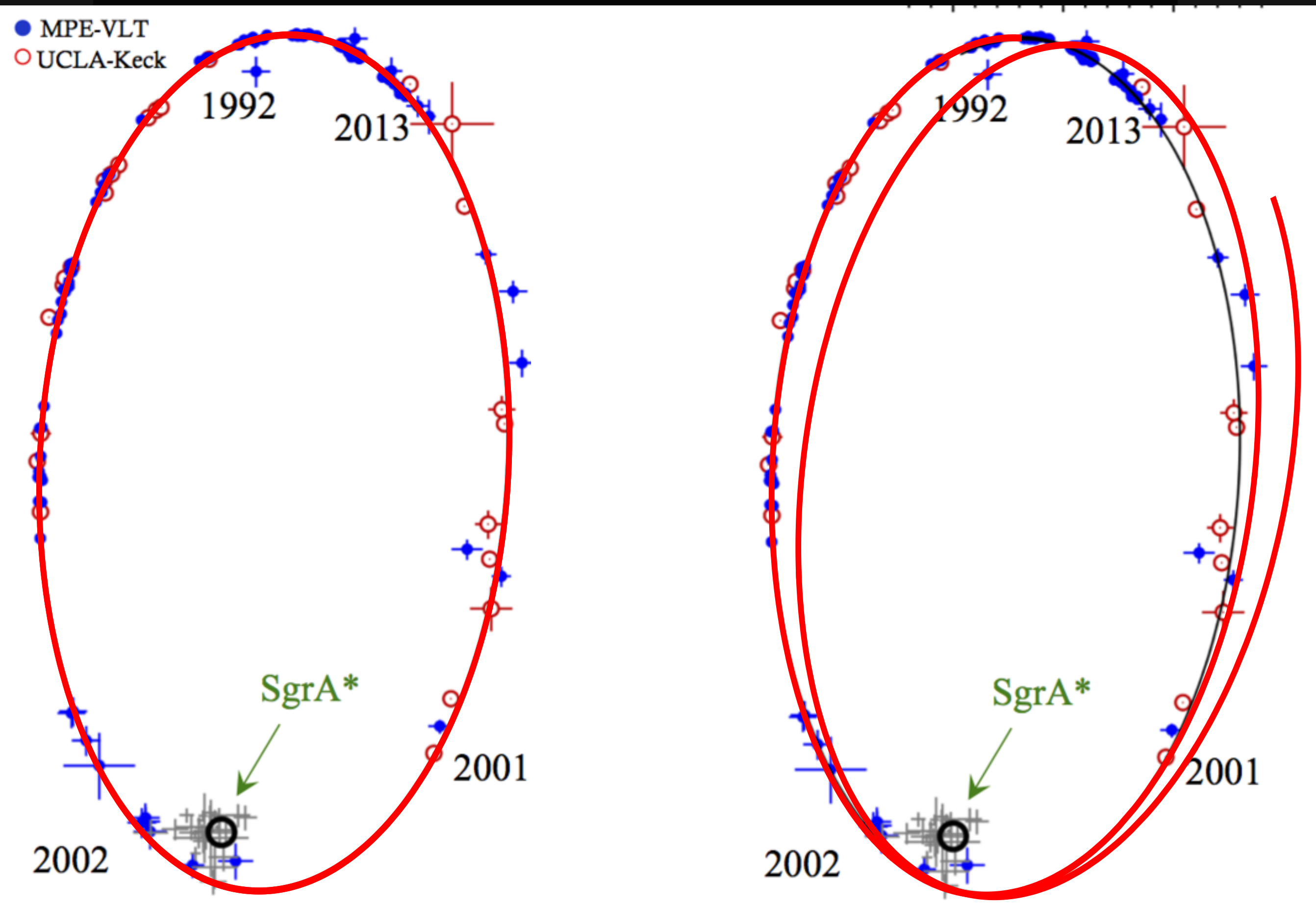
m_X

10^{-21} eV $\rightarrow$ 10^{-18} eV ?

There are complimentary observables

Bar et al 2019; Amorim et al 2019 (GRAVITY),…

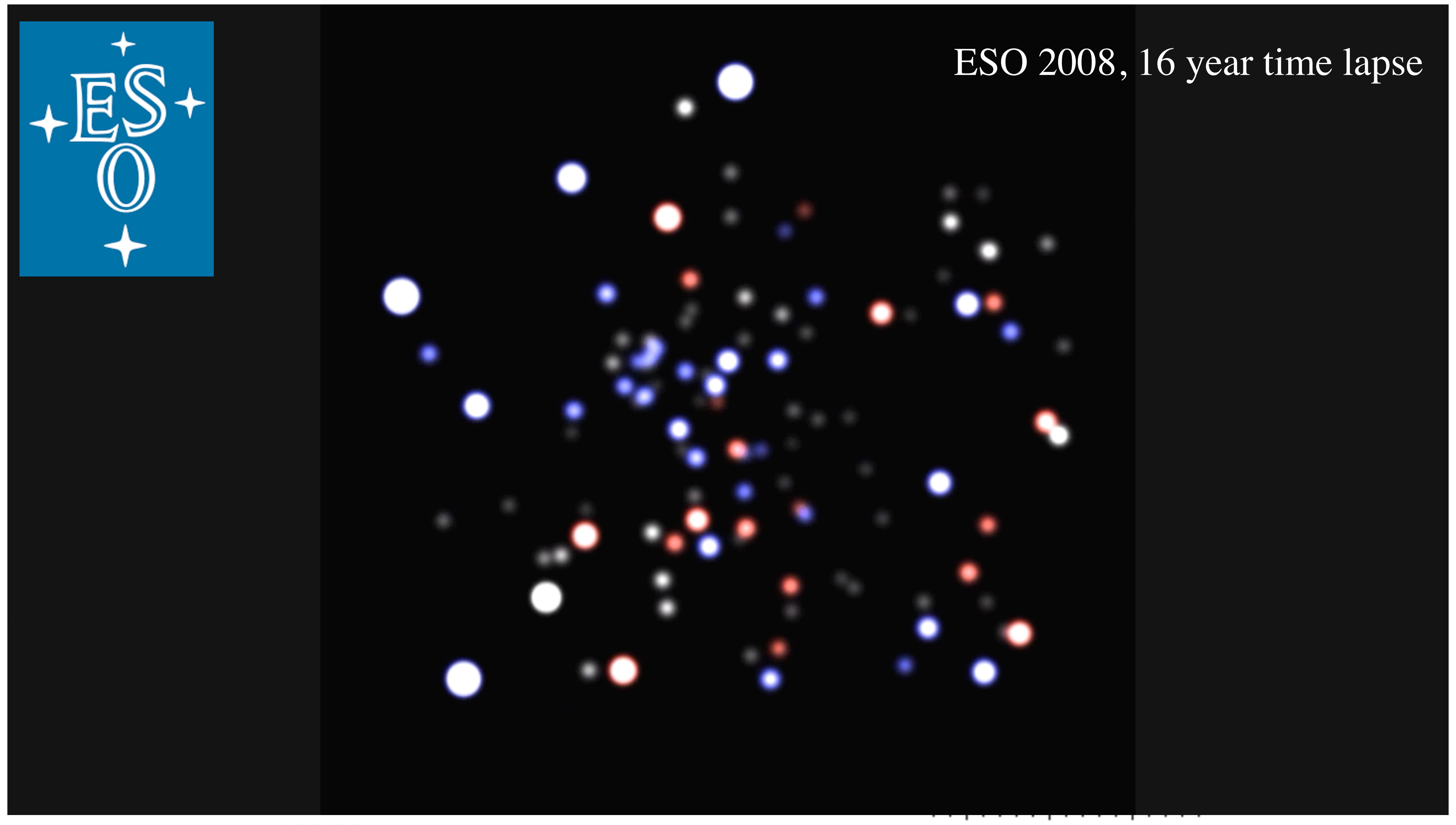




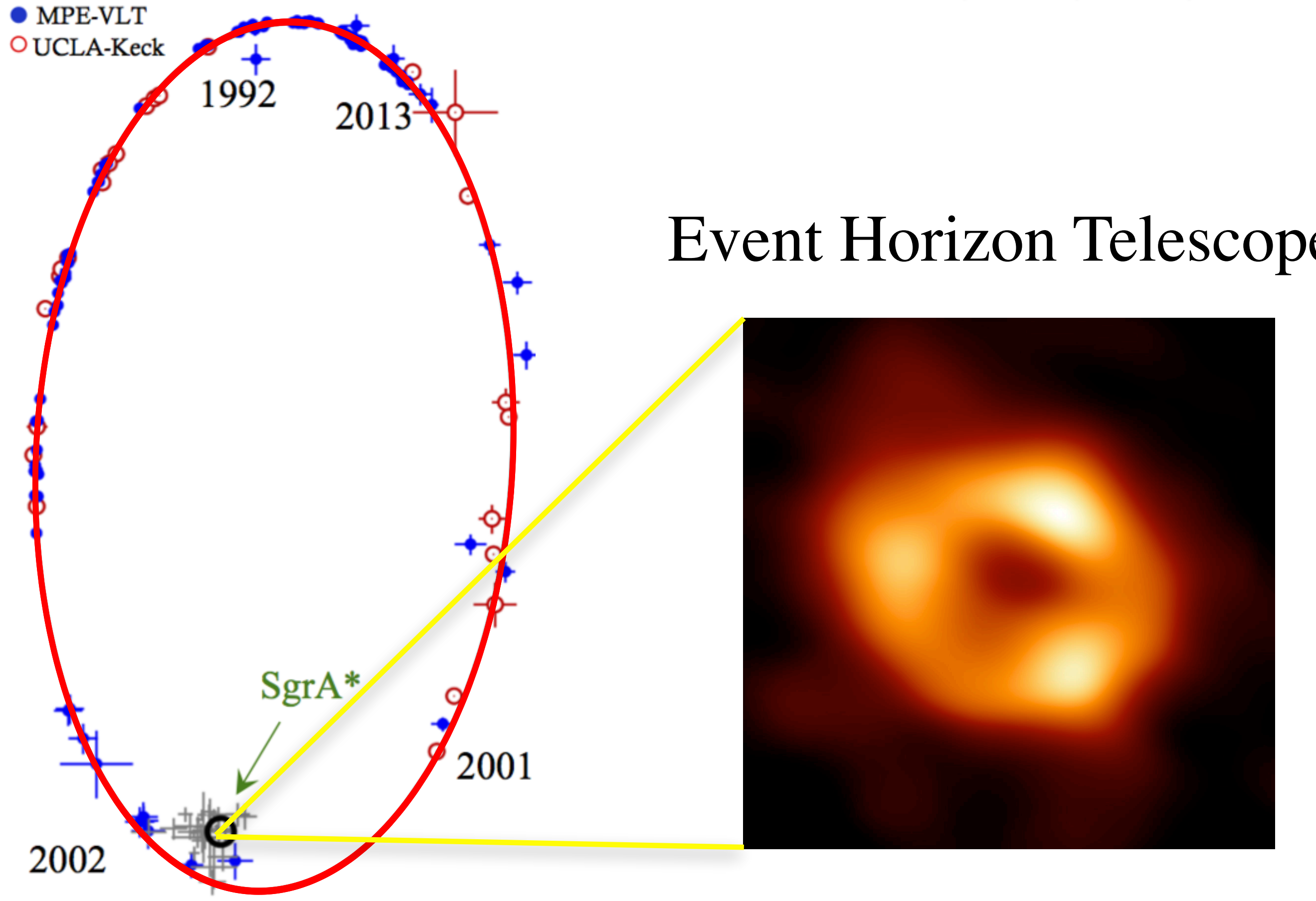
m_X

10^{-21} eV → 10^{-18} eV ?

There are complimentary observables   Bar et al 2019; Amorim et al 2019 (GRAVITY),…



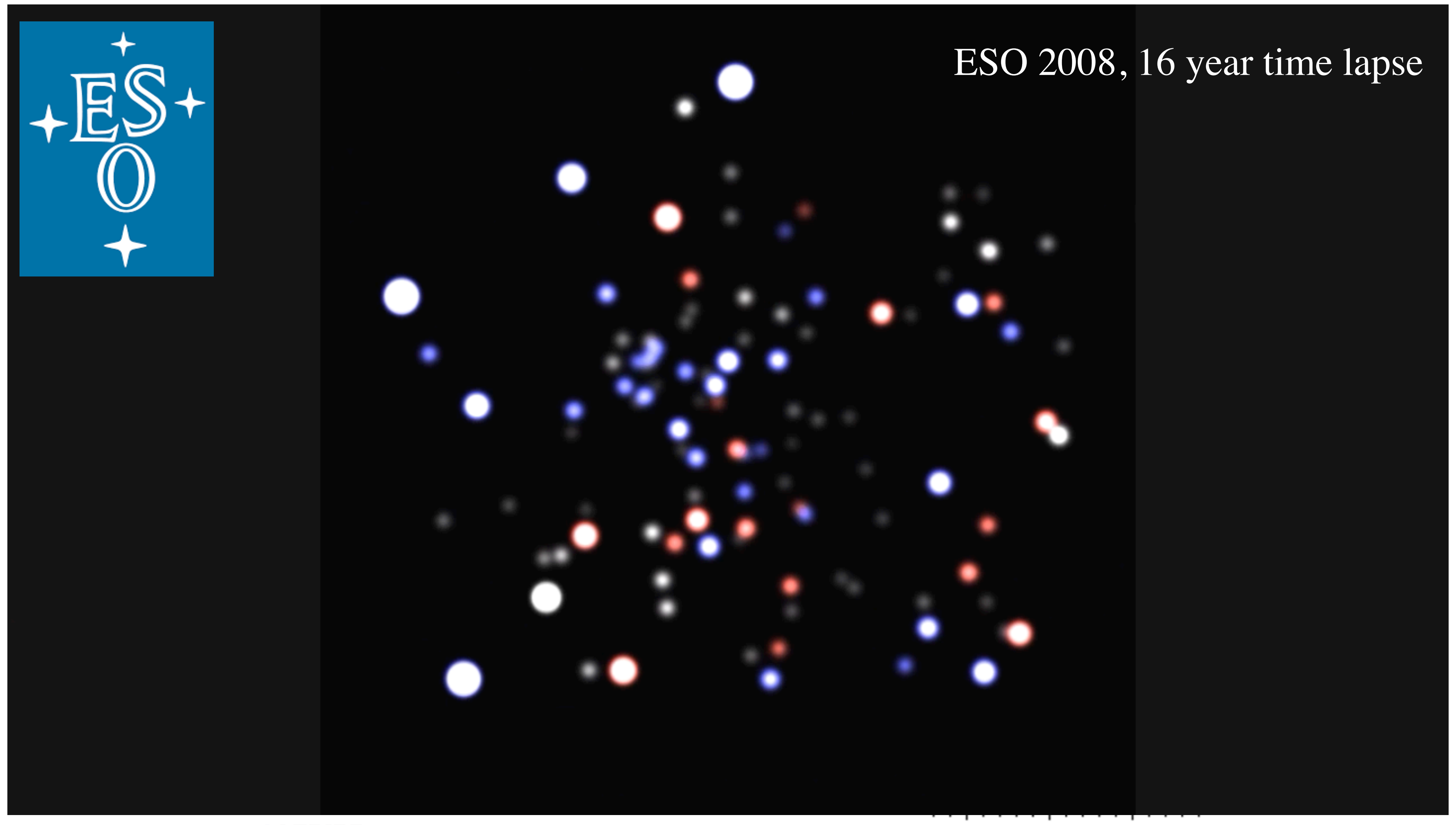
Event Horizon Telescope 2022

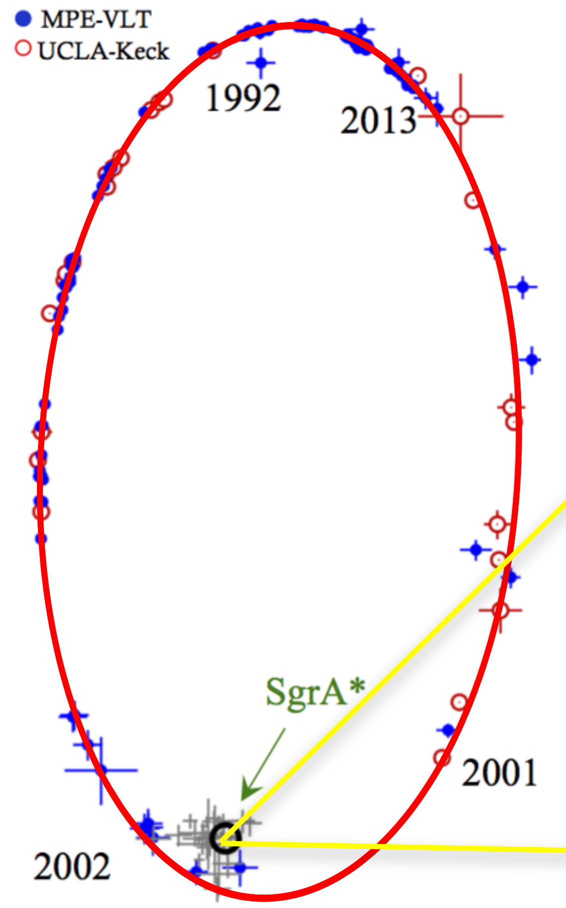


10^{-21} eV $\rightarrow$ 10^{-18} eV ?

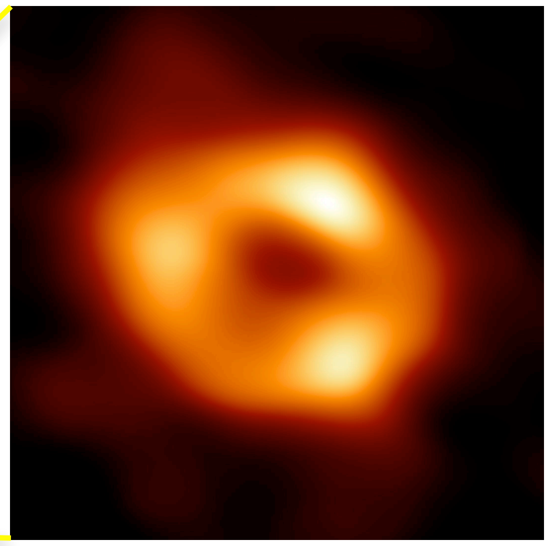
There are complimentary observables

Bar et al 2019; Amorim et al 2019 (GRAVITY),…





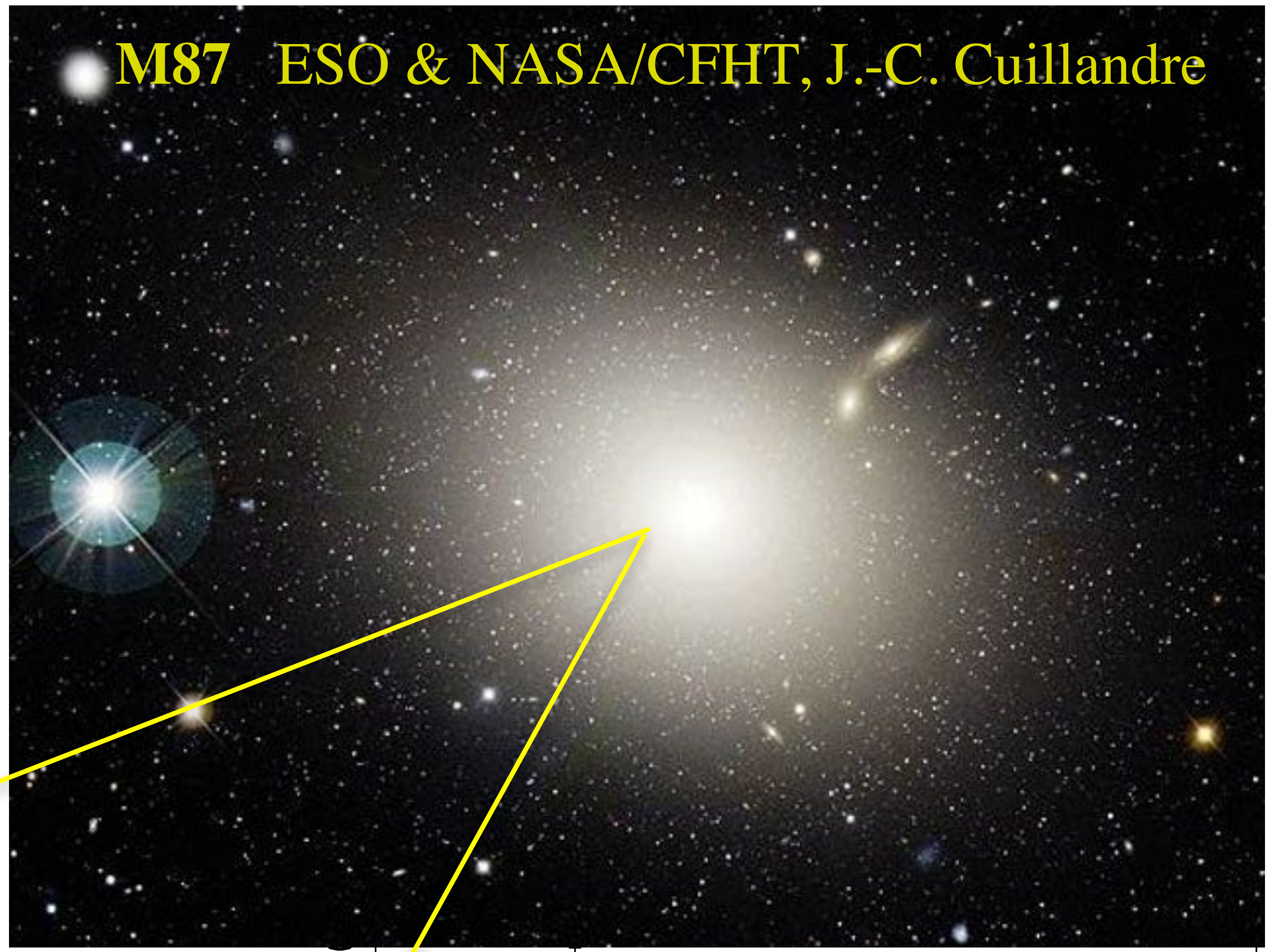
Event Horizon Telescope 2022

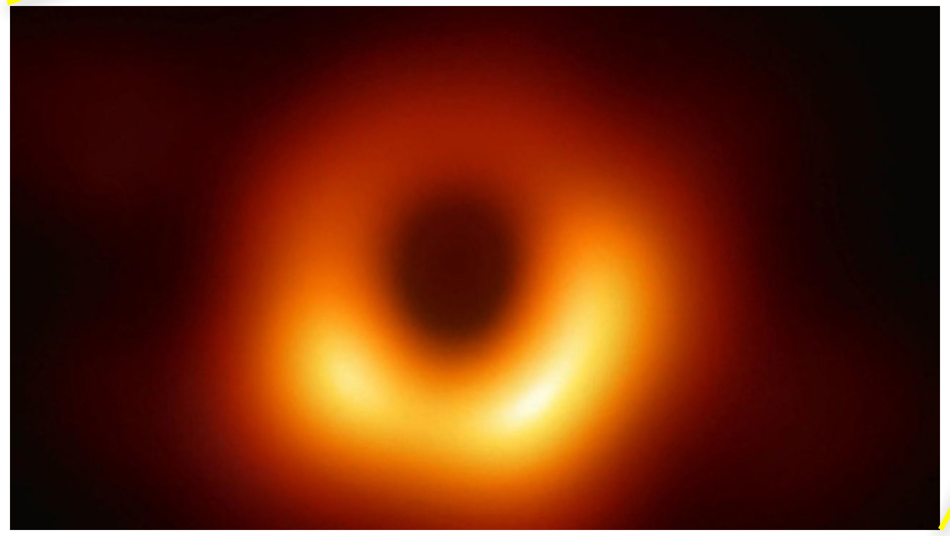


BH shadow ~ 10^{10} km

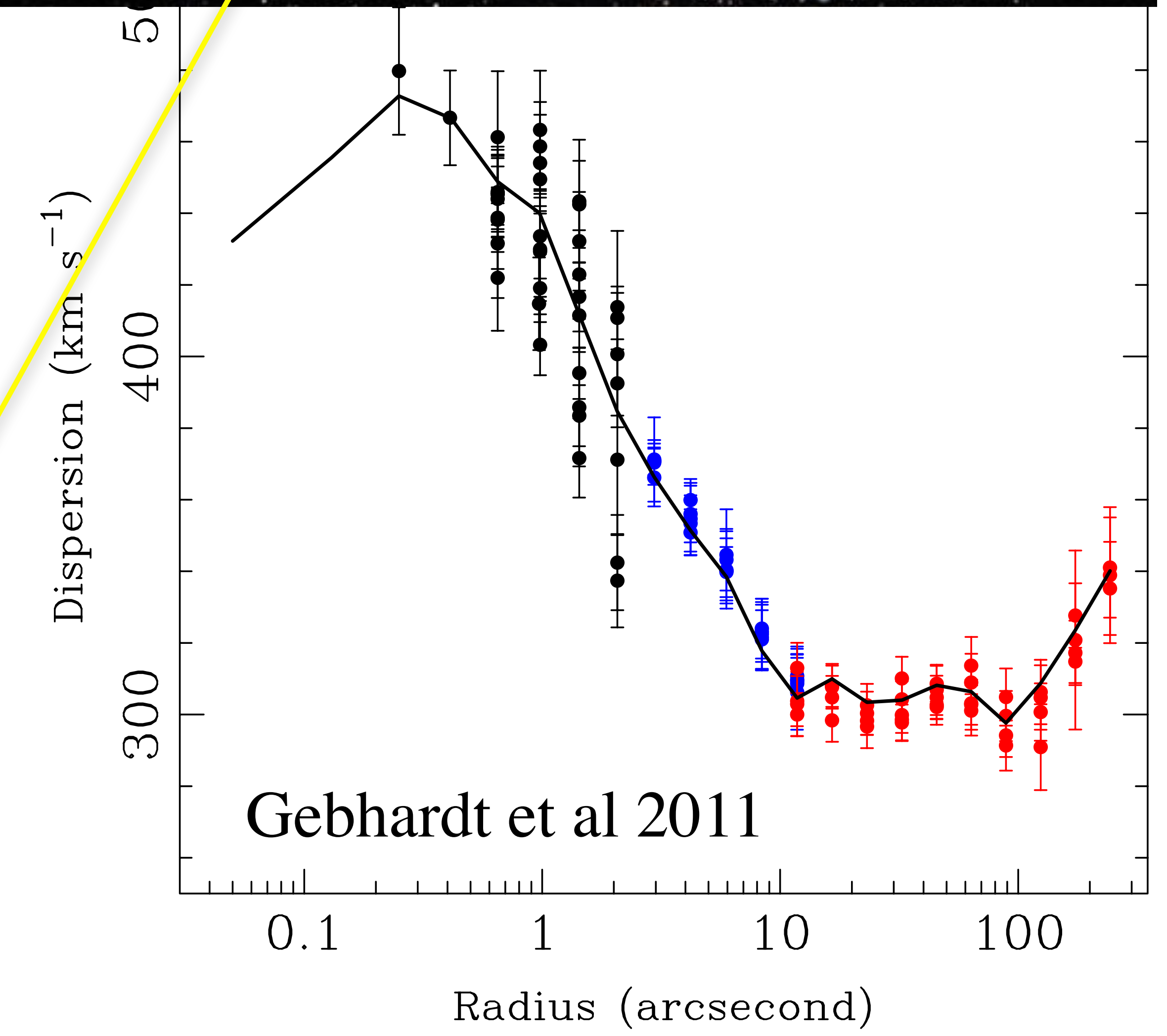
Stellar velocities ~ 10^{16} km

…Nothing in between.





Event Horizon Telescope 2019



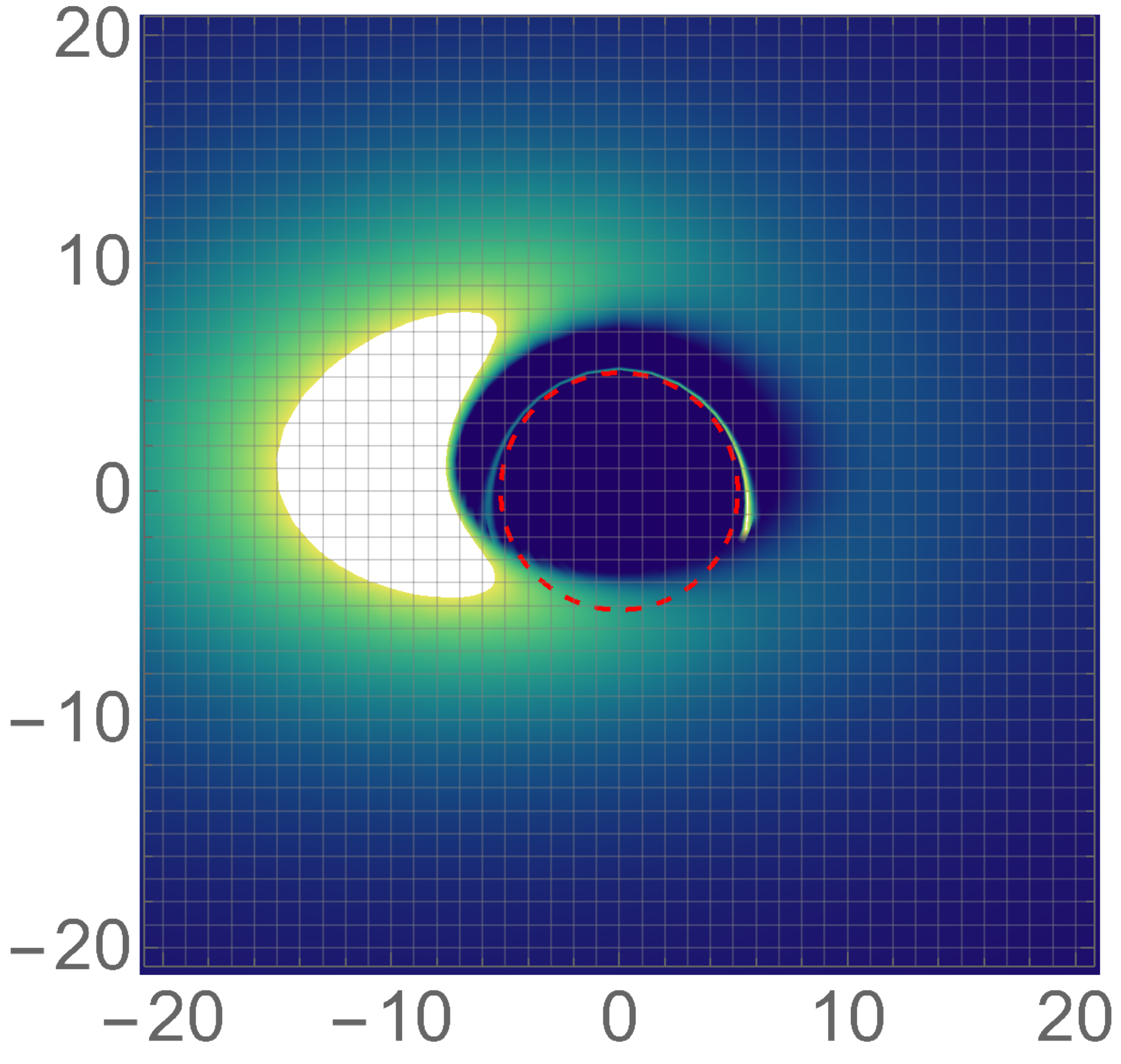
Gebhardt et al 2011

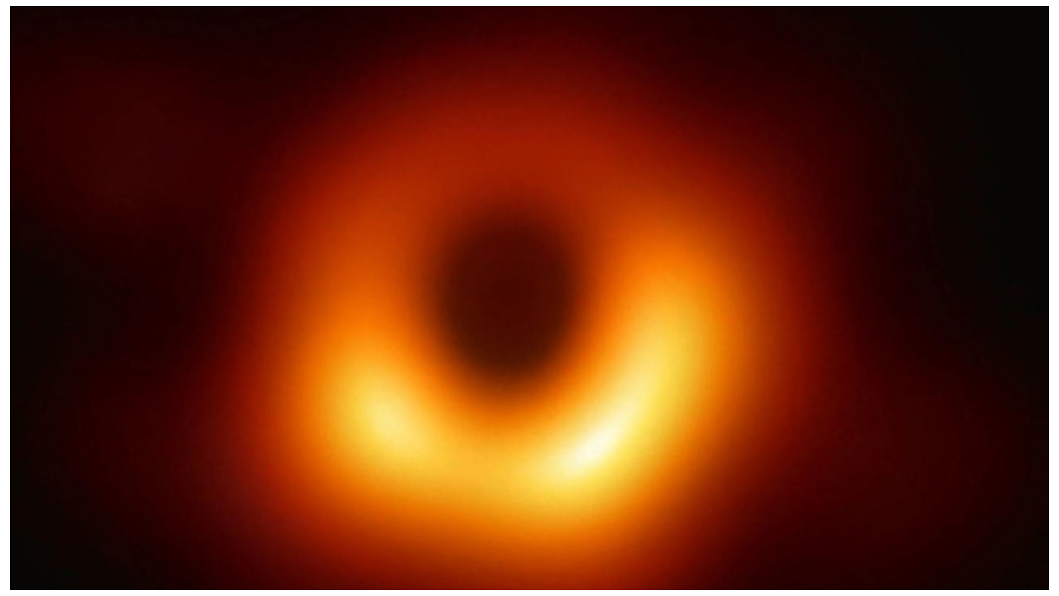
m_X

10^{-21} eV → 10^{-18} eV ?

(Luminet 1978)

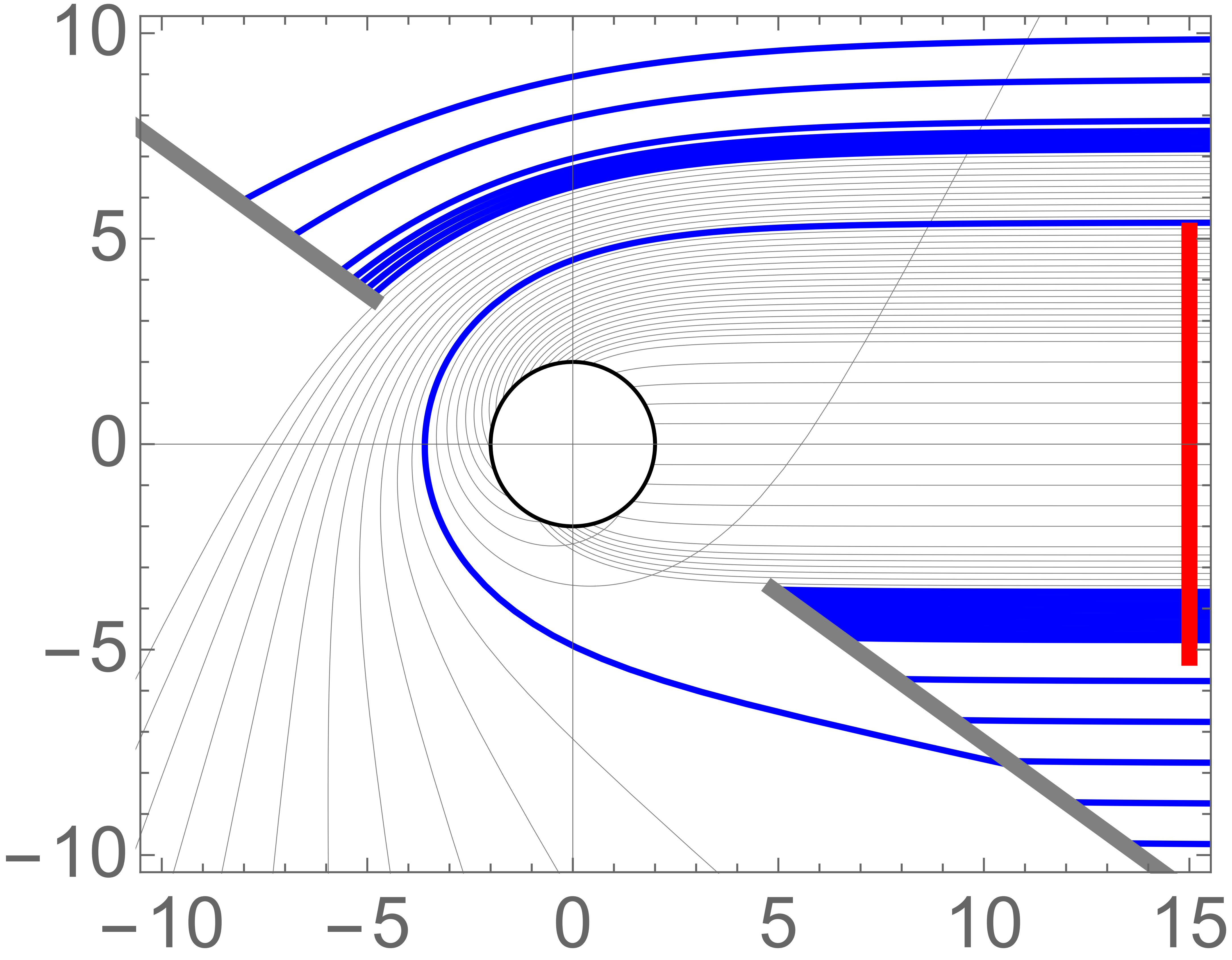
Thin, optically-thick disk





Model-dependence in accurate interpretation:

e.g. Gralla, Holz, Wald 1906.00873



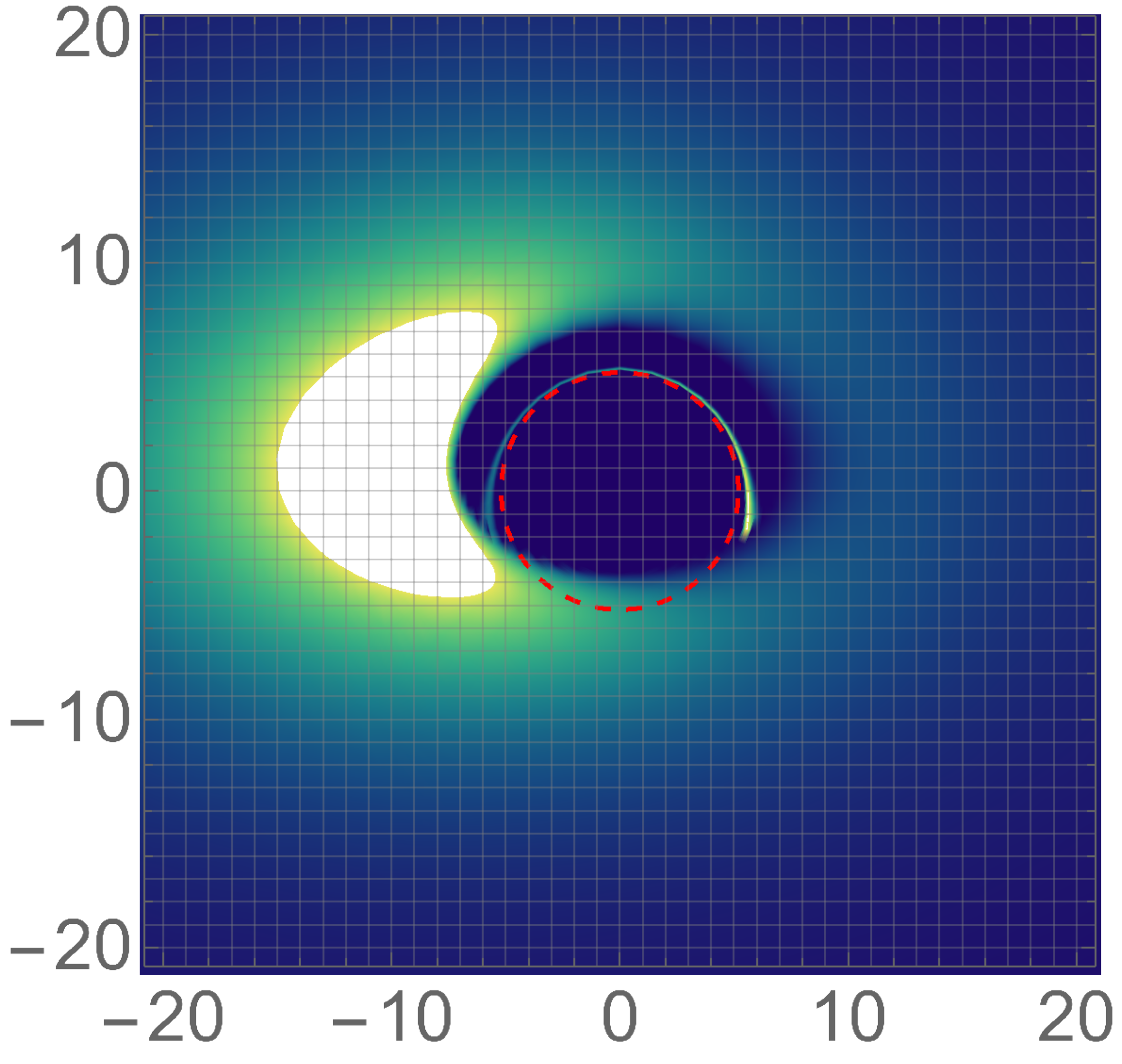
$$\left(\frac{du}{d\varphi}\right)^2 + u^2(1-2u) = \frac{1}{b^2}$$

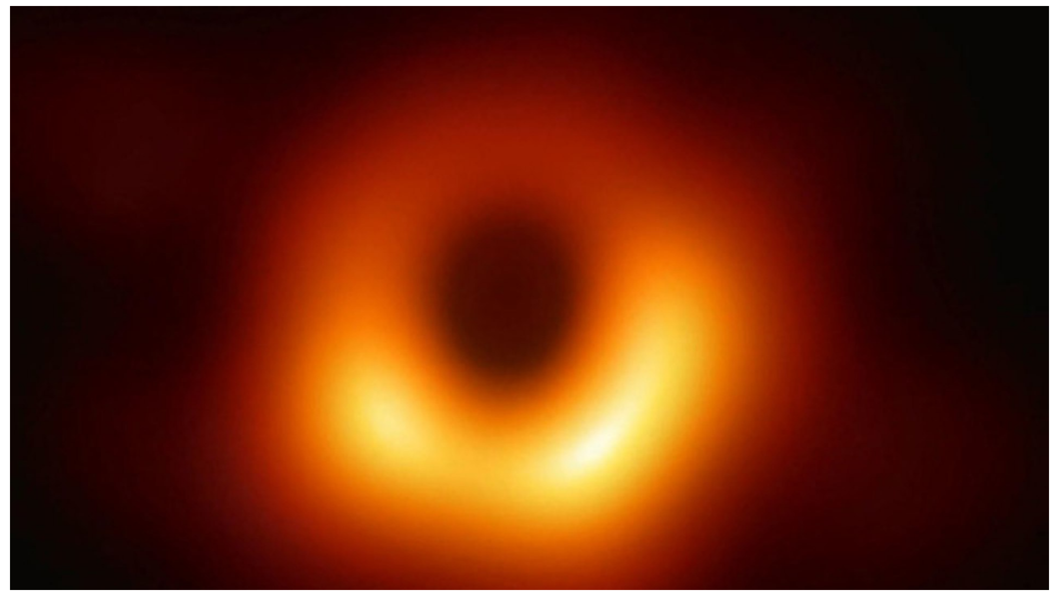
$$u = \frac{1}{r}$$ units of GM

m_X

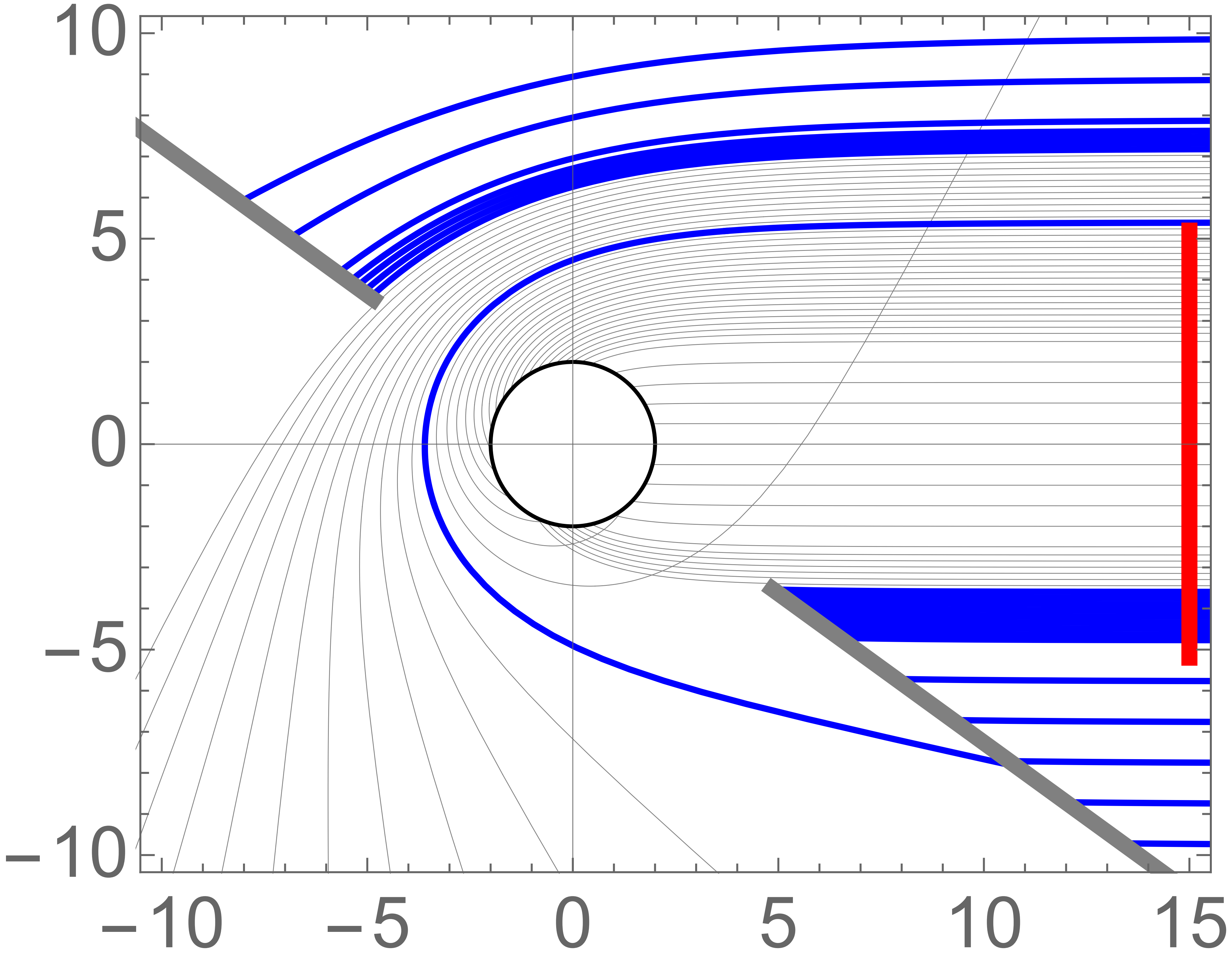
10^{-21} eV → 10^{-18} eV ?

(Luminet 1978)
Thin, optically-thick disk

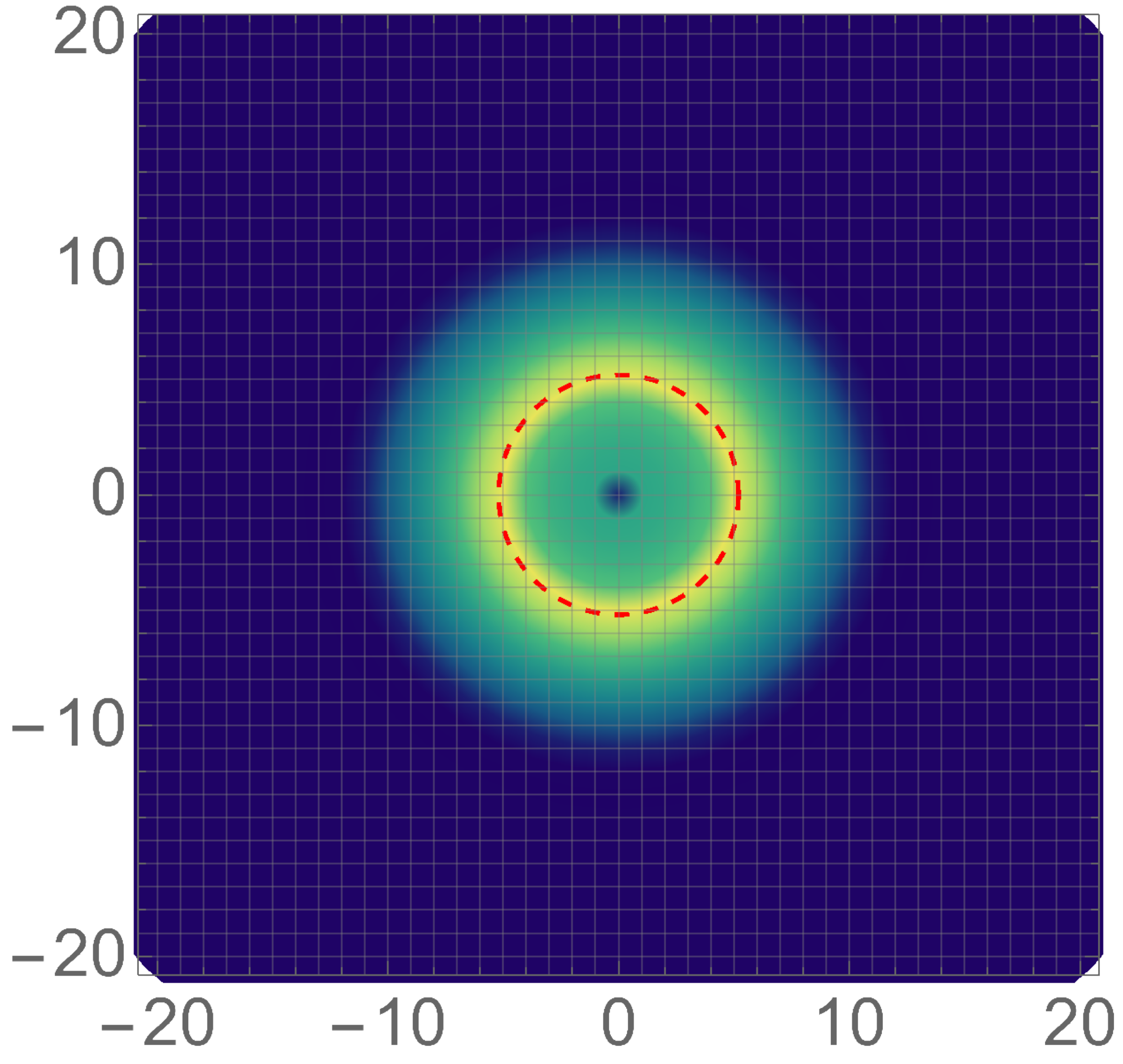




Model-dependence in accurate interpretation:
e.g. Gralla, Holz, Wald 1906.00873



(Flacke, Melia, Agol 2000)
Optically-thin spherical gas

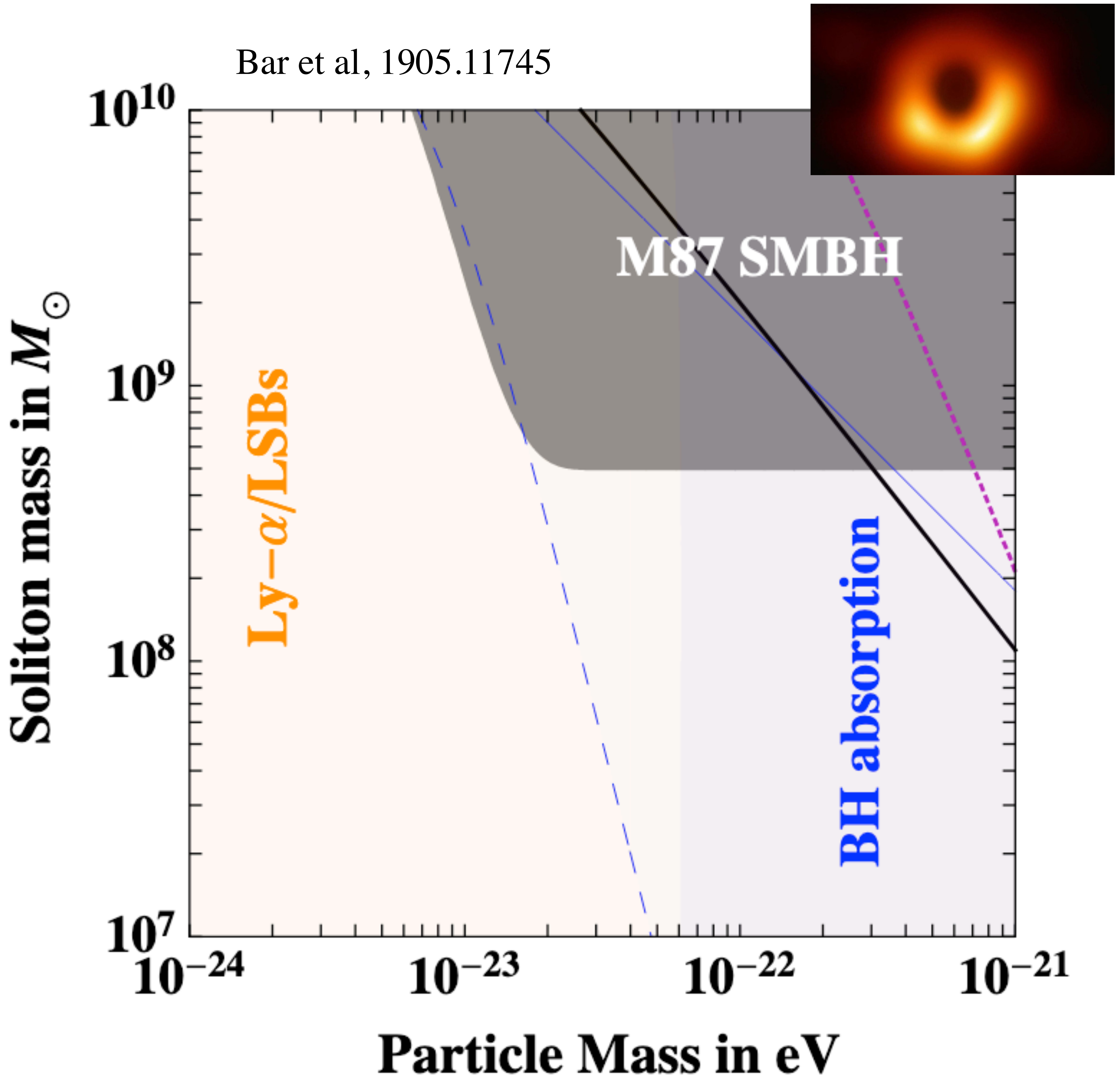


m_X

10^{-21} eV $\rightarrow$ 10^{-18} eV ?

SMBH effect: e.g. Annulli, Cardoso, Vicente 2009.00012

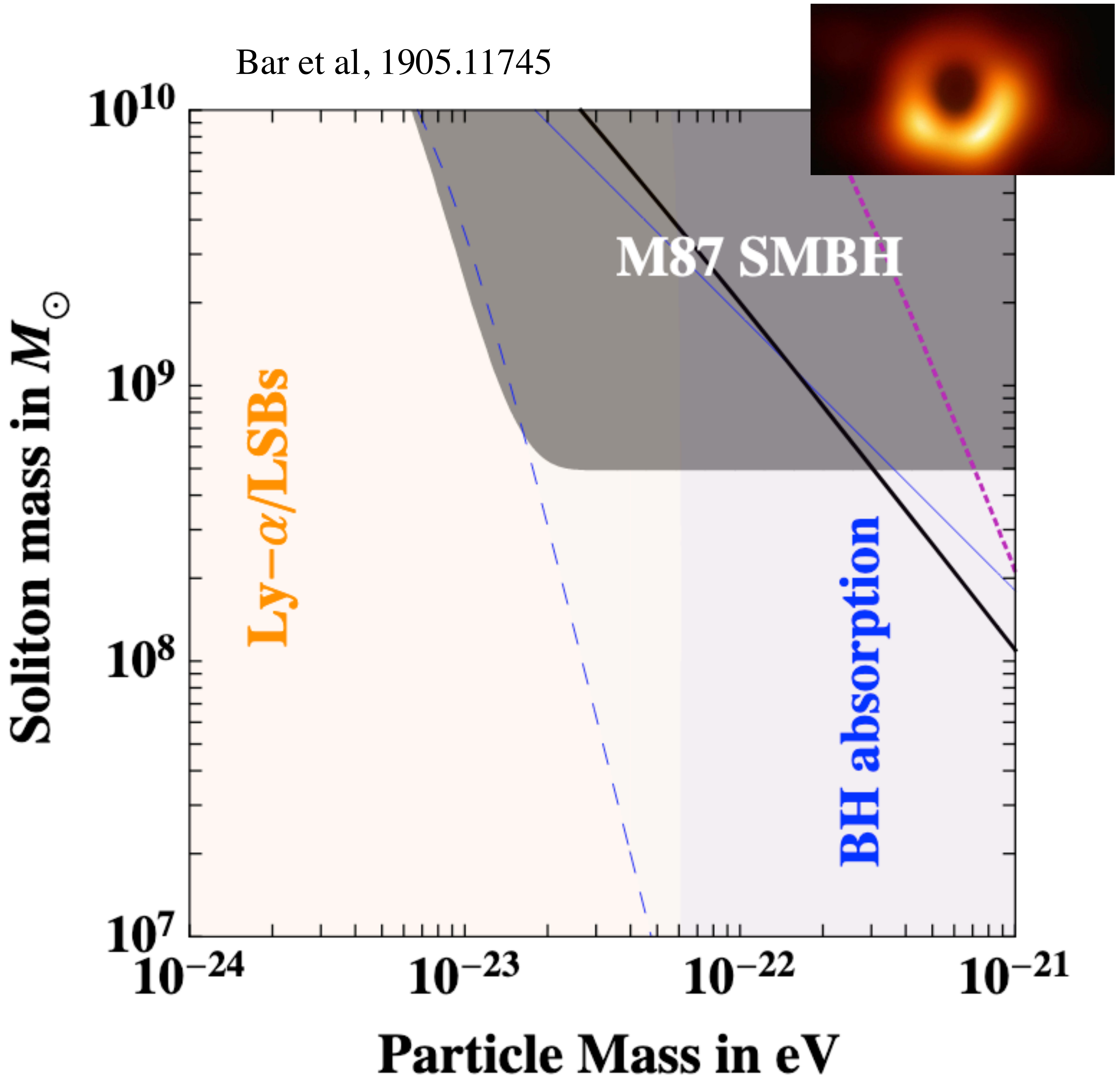
Bar et al, 1905.11745

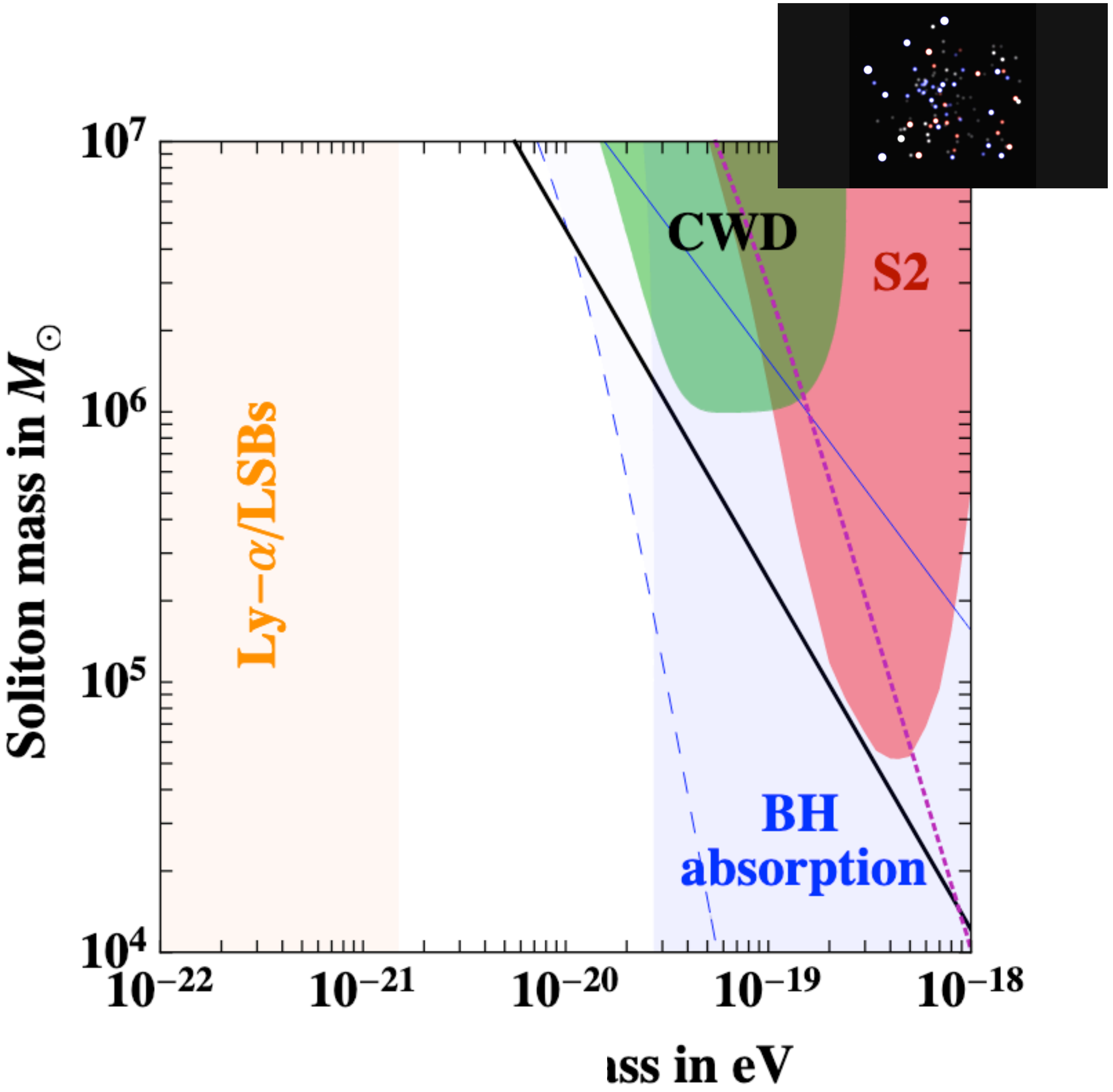


10^{-21} eV → 10^{-18} eV ?

SMBH effect: e.g. Annulli, Cardoso, Vicente 2009.00012

Bar et al, 1905.11745





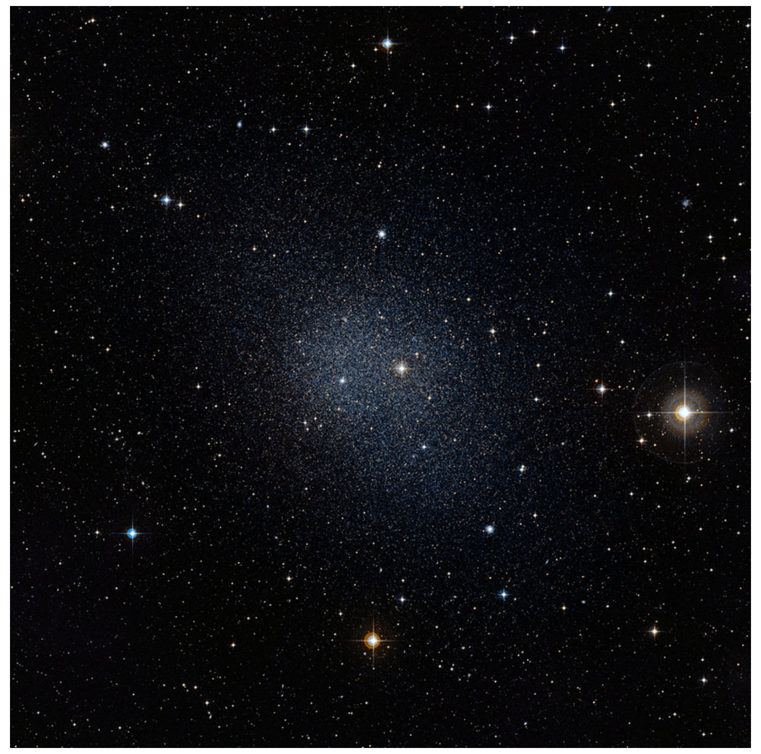
Gravity alone

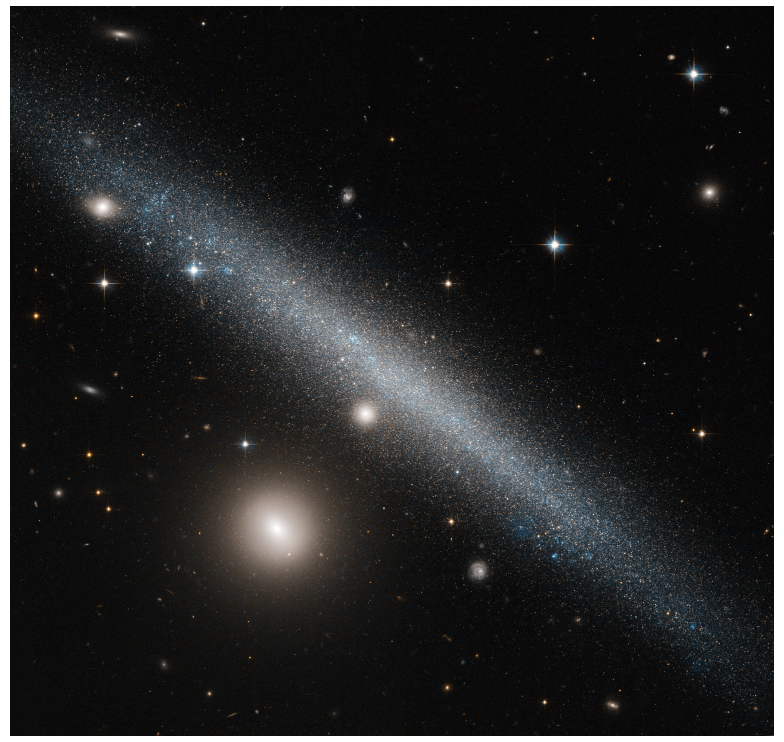
m_χ

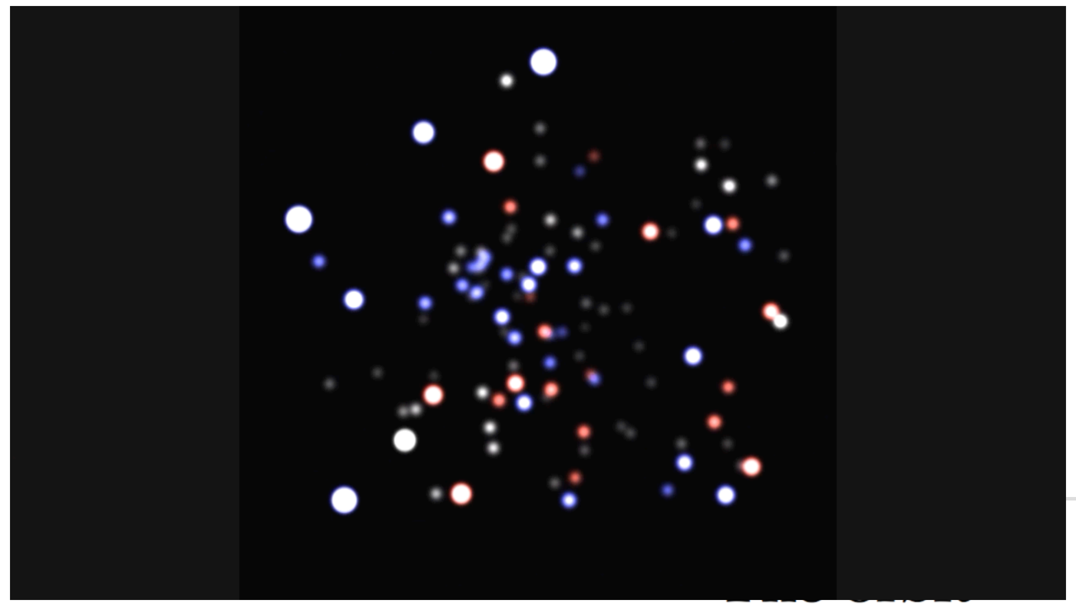
10^{-21} eV

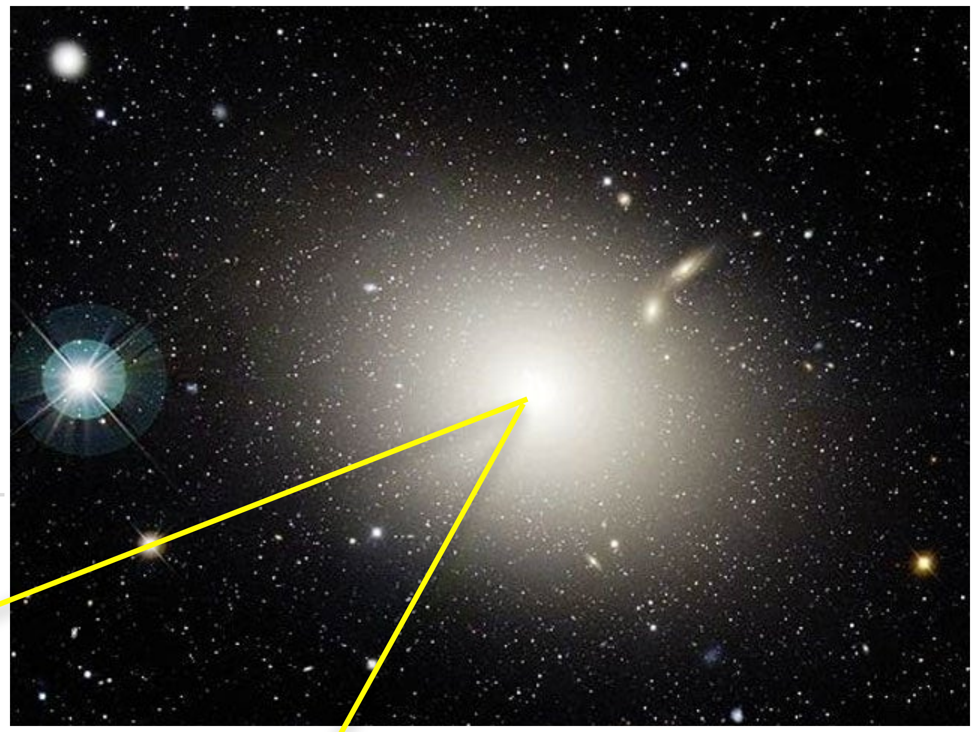
$10^{-10}\ \mathrm{M}_\odot \sim 10^{56}$ eV

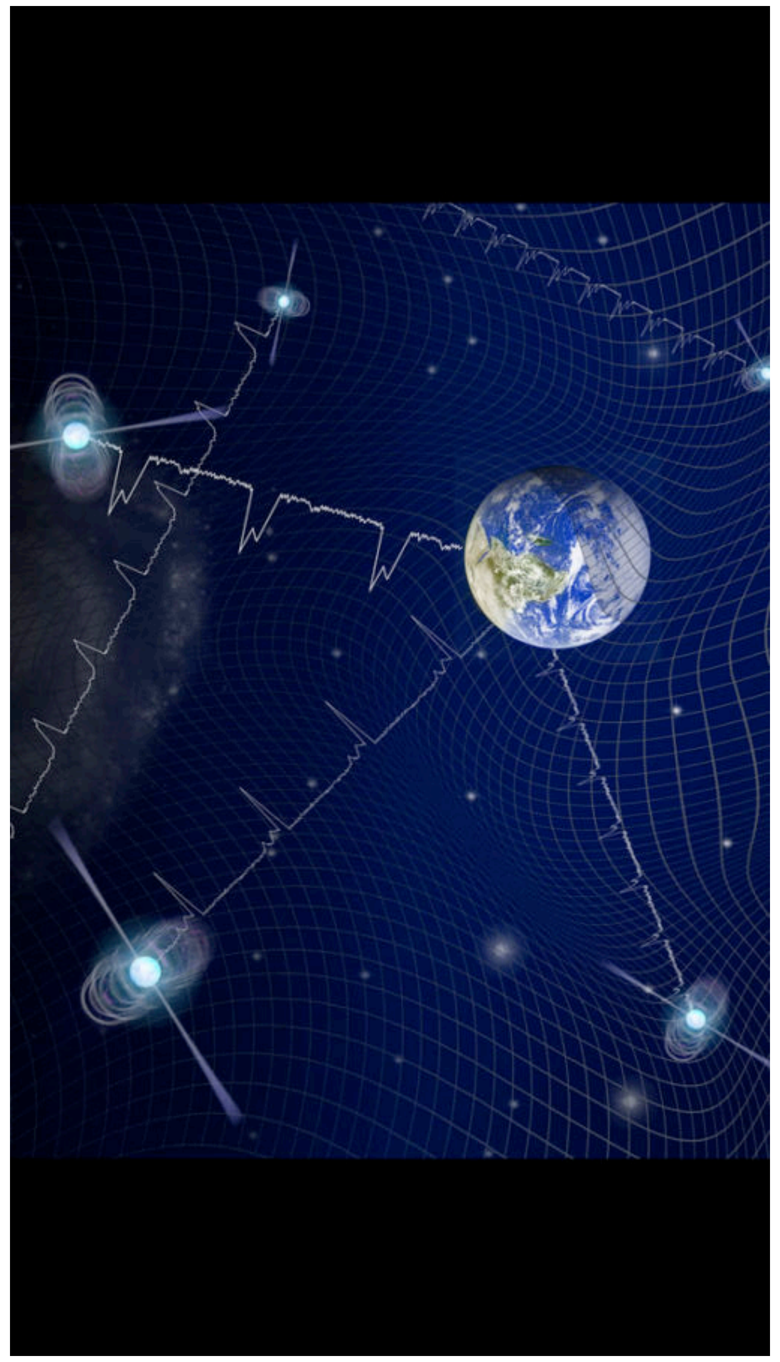
Ultralight dark matter

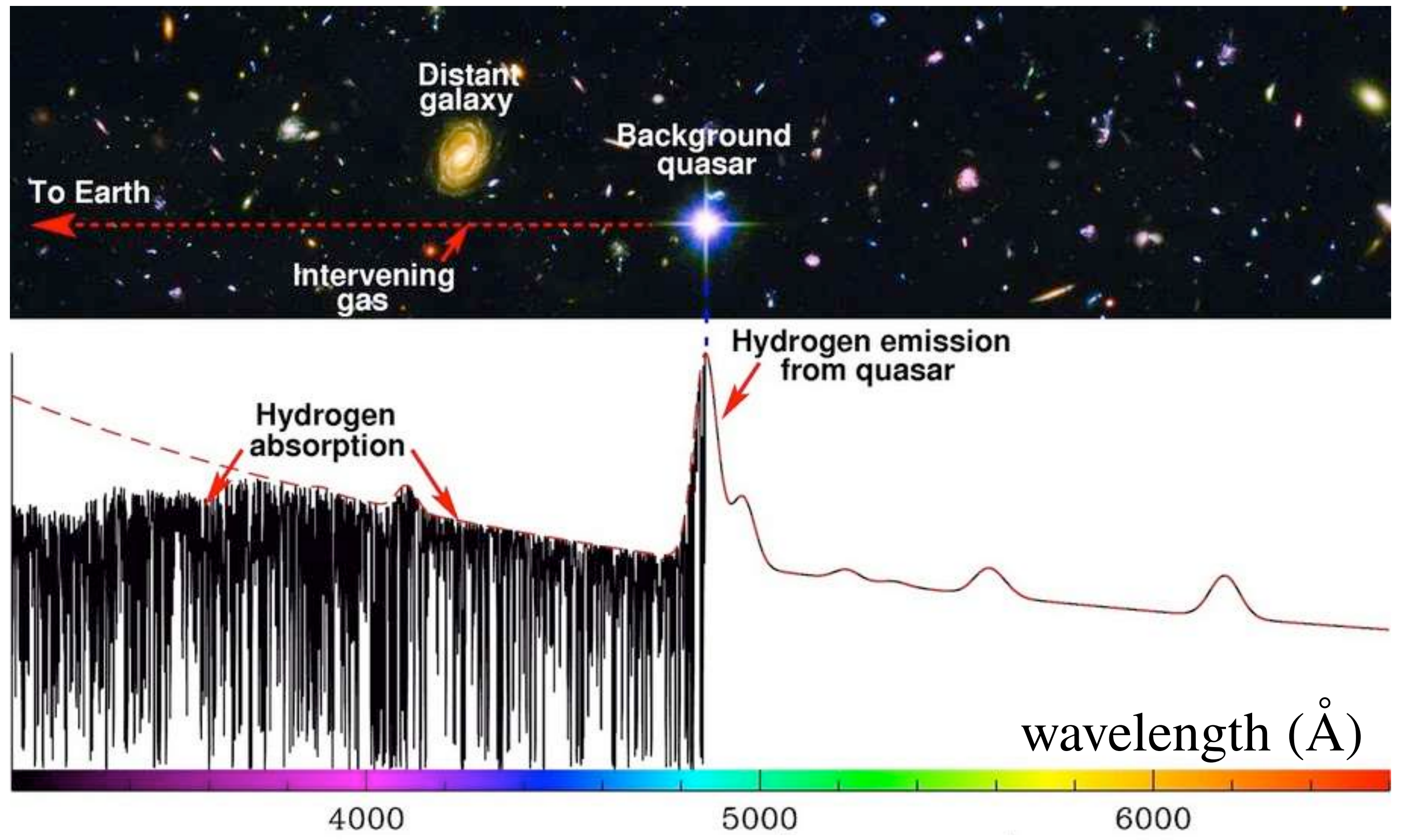


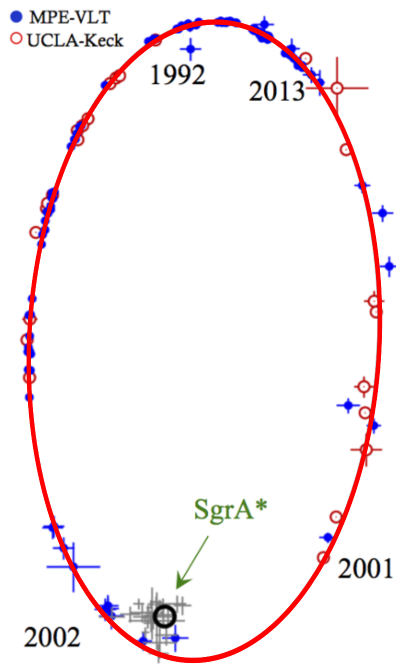


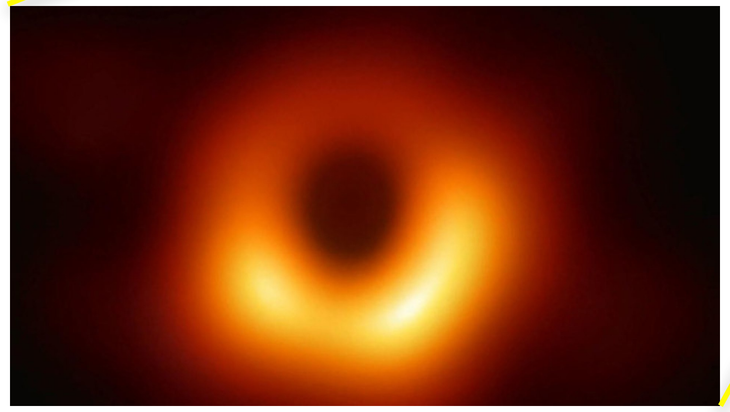


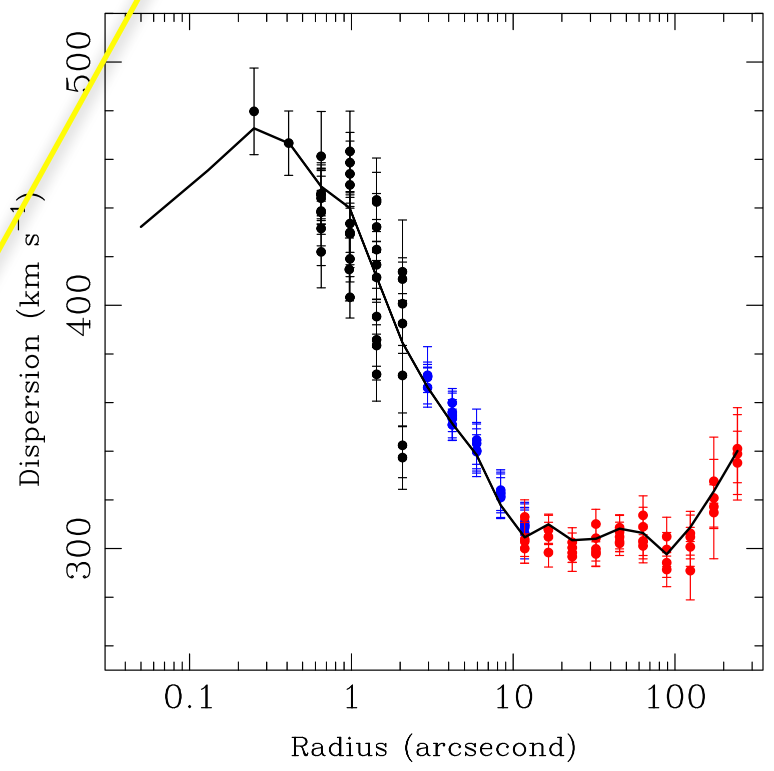




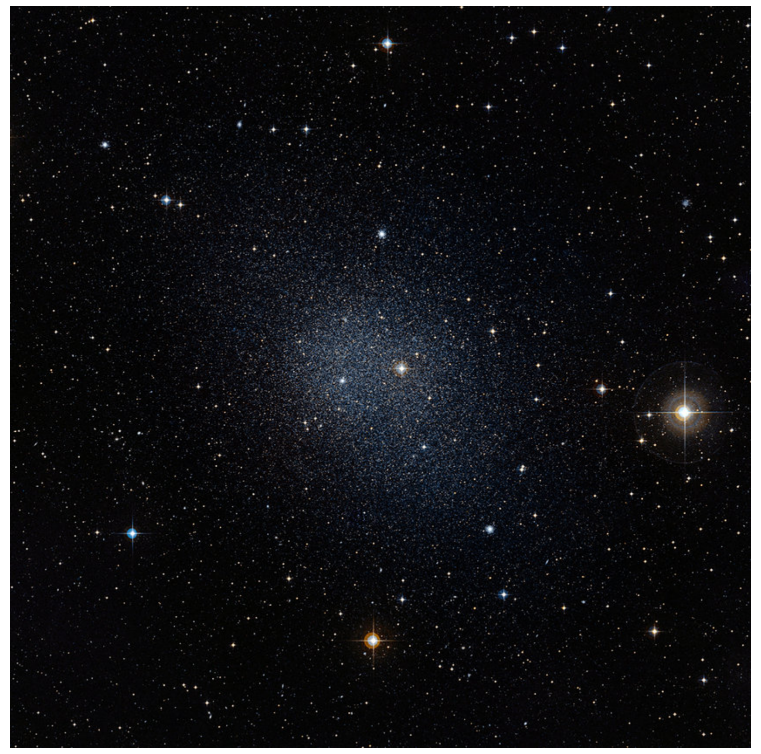


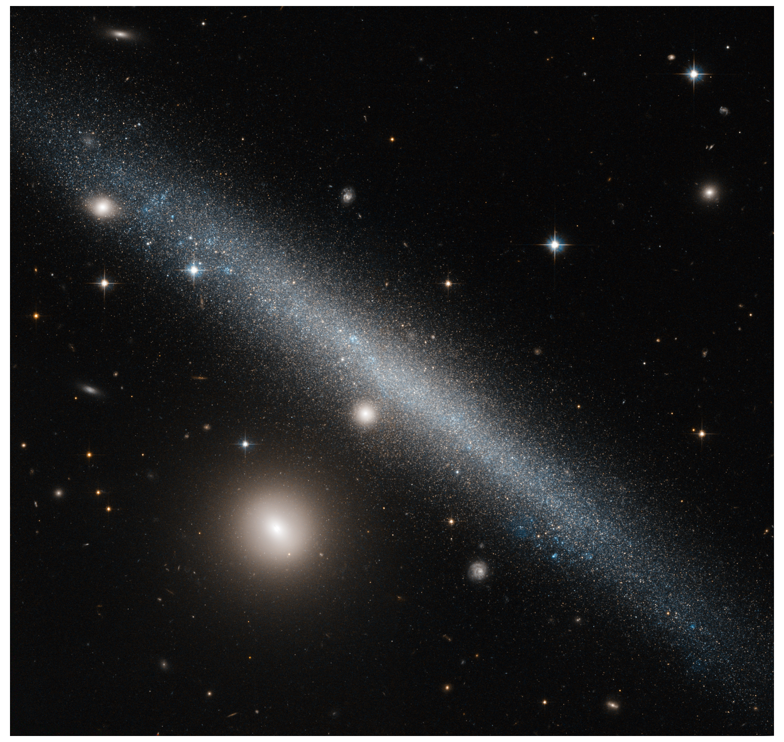


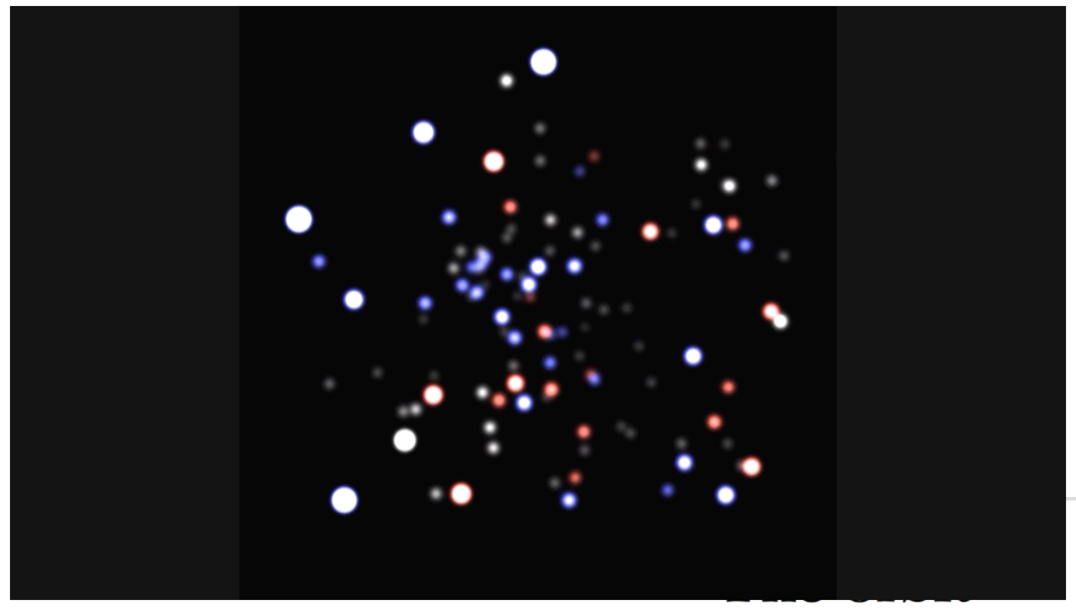


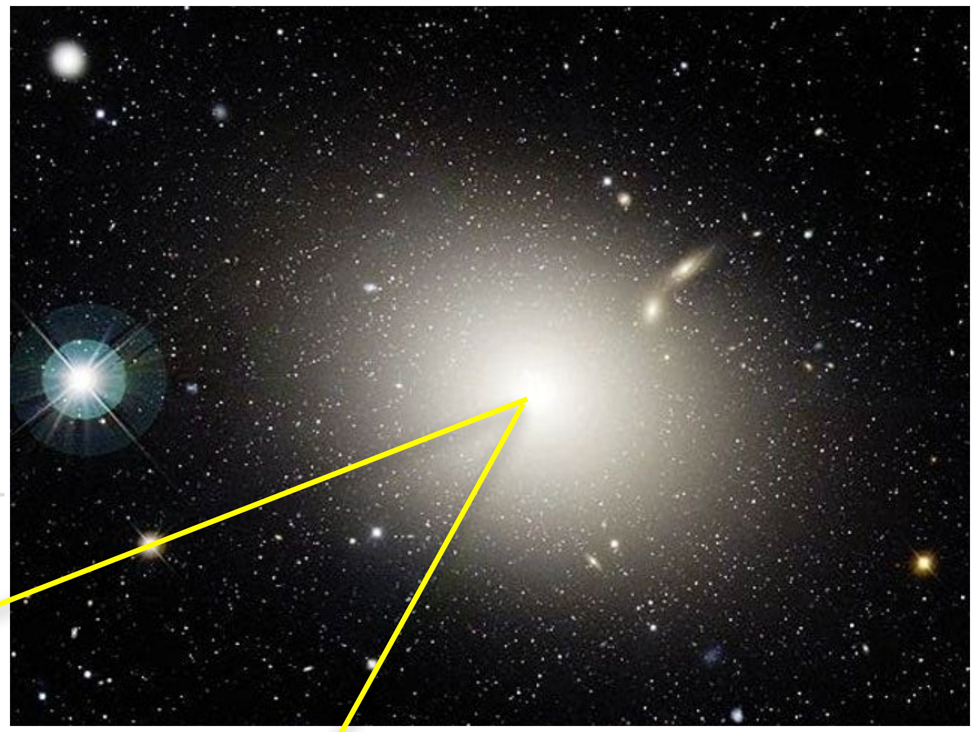


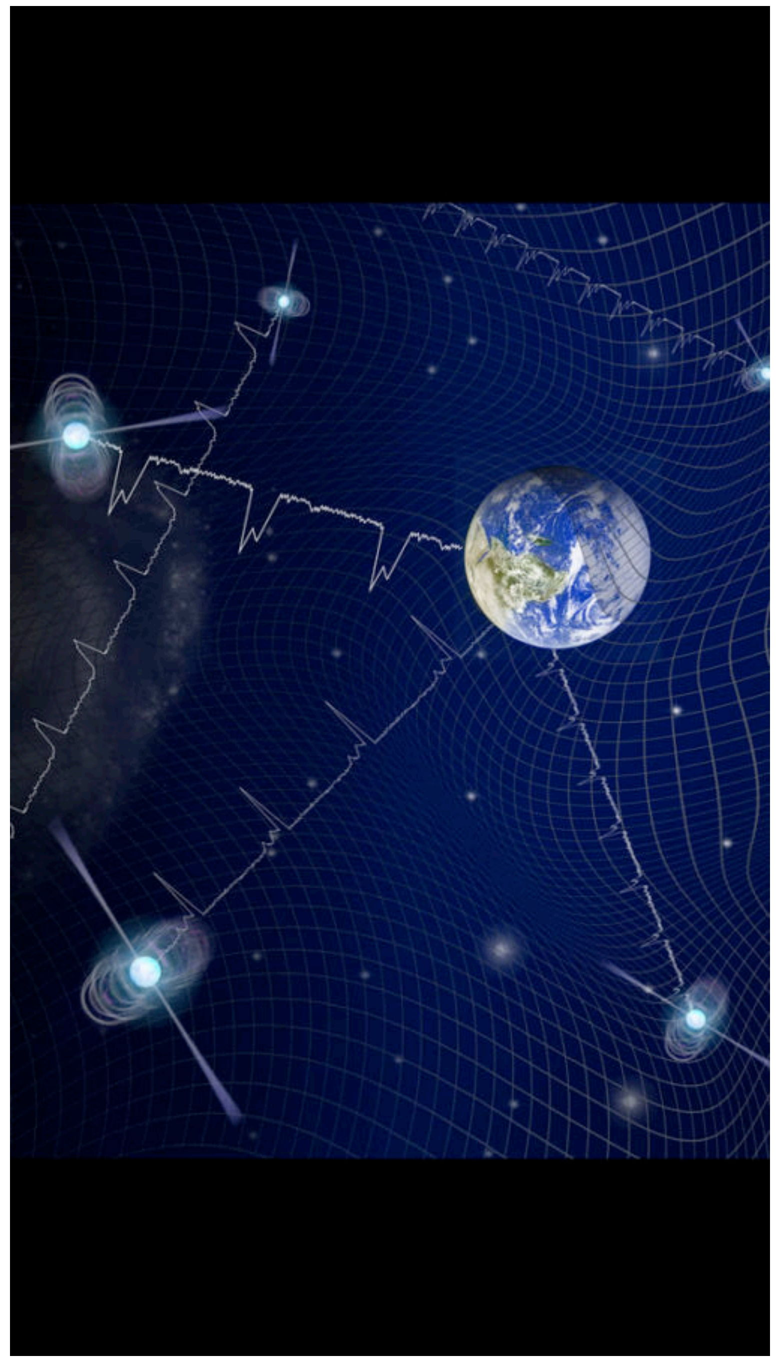
Thank you!

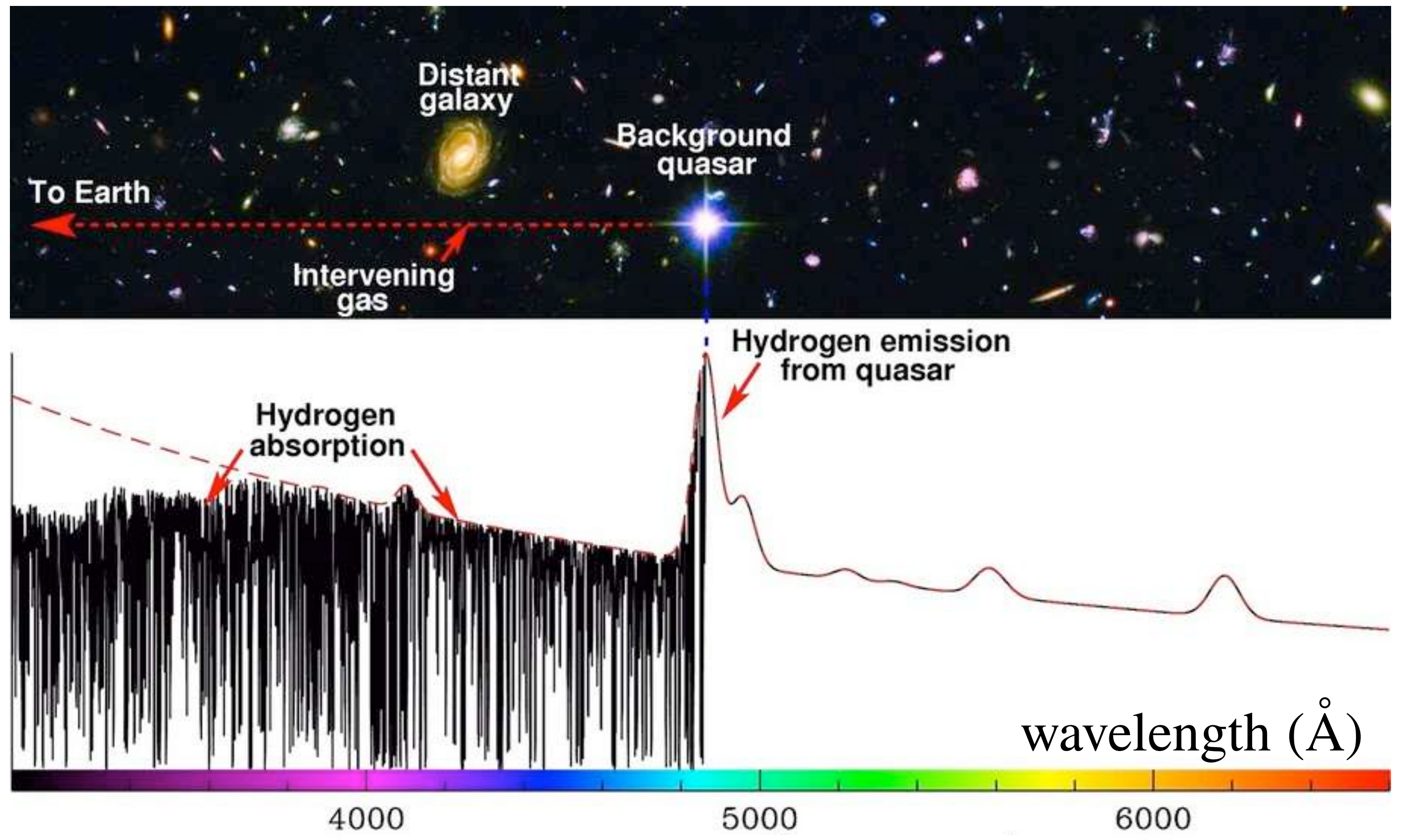


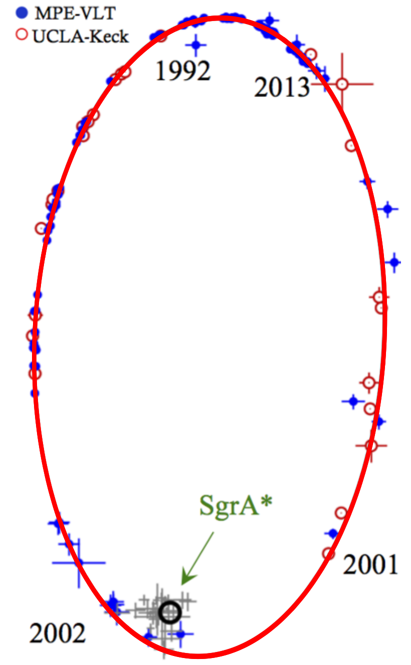


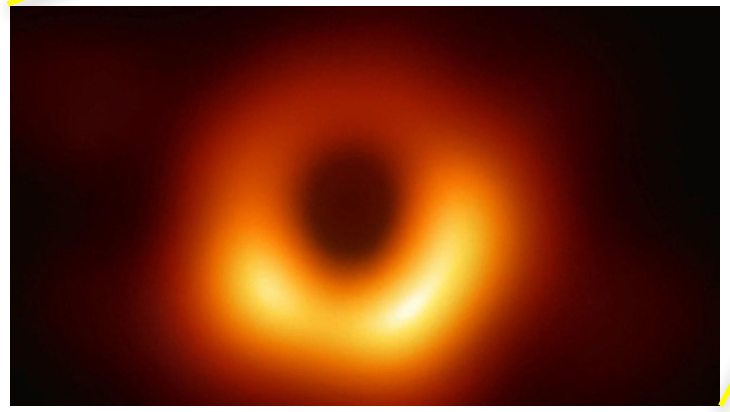


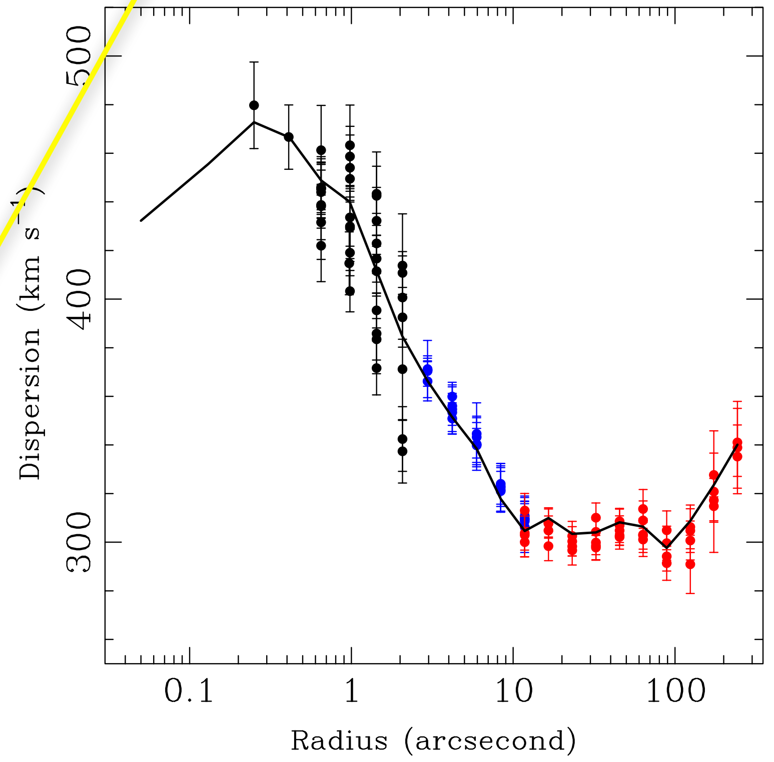





Distant galaxy
Background quasar
To Earth
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
wavelength (Å)
4000
5000
6000


MPE-VLT
UCLA-Keck
1992
2013
SgrA*
2001
2002




500
400
300
Dispersion (km s⁻¹)
0.1
1
10
100
Radius (arcsecond)

Some facts about solitons

Continuous family of ground state solutions,
characterised by one parameter

Let $\chi_1(r)$ be defined to satisfy $\chi(0) = 1$, vanishing at infinity w/ no nodes.

$$M_1 = \frac{M_{pl}^2}{m} \int_0^\infty dr r^2 \chi_1^2(r)$$
$$\approx 2.79 \times 10^{12} \left(\frac{m}{10^{-22}\ \mathrm{eV}} \right)^{-1} \mathrm{M}_\odot$$

Other solutions obtained by scaling

$$\chi_\lambda(r) = \lambda^2 \chi_1(\lambda r),$$
$$\Phi_\lambda(r) = \lambda^2 \Phi_1(\lambda r),$$
$$\gamma_\lambda = \lambda^2 \gamma_1,$$

$$M_\lambda = \lambda M_1,$$
$$x_{c\lambda} = \lambda^{-1} x_{c1}$$